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EFFECT OF DISTRIBUTION AND SHIFT IN DISTRIBUTION OF PRACTICE WITHIN A SINGLE TRAINING SESSION[1]

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When *S*s are trained on a psychomotor task with different degrees of spacing of trials, the performance curves show two notable characteristics. First, during the early trials there is apparently some adjustment to the particular conditions of distribution holding. During this phase of performance, differences between acquisition curves resulting from distribution of practice become established with massed practice producing a lower mean level than distributed practice. Second, trial-to-trial increments in the later trials tend to be constant for all distribution groups and independent of the conditions of distribution of practice. Snoddy (**7, 8**) was apparently the first to call attention to these characteristics of motor performance curves under varying conditions of practice distribution. These characteristics suggest a descriptive equation for psychomotor acquisition data as a function of distribution of practice. The equation is as follows:

$$P = M(1 - e^{-iT}) + bT \qquad (1)$$

where:

P is a performance measure,
T is number of trials,
e is the base of natural logarithms,
M is the limit for the exponential component and is assumed to increase as a negatively accelerated function of the interval between trials,
i is the rate of growth for the exponential component and assumed to be a negatively accelerated decay function of the interval between trials,
b is a parameter independent of intertrial interval.

This equation has been used to generate five hypothetical curves which are presented in Fig. 1. These curves represent performance for increasing values of M and decreasing values of i. It will be noted upon inspection of Equation 1 or the curves plotted in Fig. 1, that the over-all level of performance is determined by the value for M. When the value of the exponential term becomes negligible with

[1] The experimental work for this study was performed as part of the United States Air Force Human Resources Research and Development Program. The opinions or conclusions contained in this report are those of the authors. They are not to be construed as reflecting the views or indorsement of the Department of the Air Force.

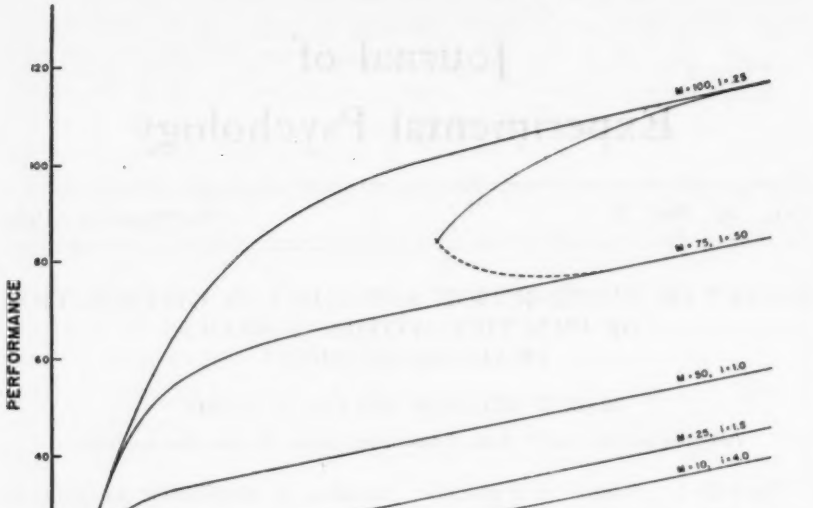

FIG. 1. Hypothetical acquisition and shift curves for selected values of M and i. The values for M and i are indicated on each curve. The four upper curves have been adjusted to the origin of the lowest performance curve. The shift from distributed to massed practice is indicated by a dotted line; the shift from massed to distributed practice is indicated by a solid line.

increasing trials, the separation of the performance curves will be invariant throughout continuing trials. This follows since $M(1 - e^{-iT})$ will approach M as trials increase. Under these circumstances Equation 1 will tend to the form

$$P = M + bT. \qquad (2)$$

When this is true, the separation of any two curves will be given by the difference between M values for the two generating equations. Also the form of the curve will become essentially linear and the trial-to-trial increments will be determined by the value for b, which is independent of distribution.

With very brief or no intertrial rest interval, the value for M will be at a minimum and the value for i at a maximum. Under these conditions the initial curvilinear segment of the performance curve can be negligible and the performance curve tends to be linear throughout all trials. When trials are widely distributed, the initial curvilinear segment for the performance curve will have greater prominence.

In connection with the hypothesis just described a question arises as to the nature of the performance curve when the conditions of distribution of practice are changed during a series of trials within a single session. The

simplest approach would be to make an additional assumption and deduce the form of these performance shift curves from Equation 1. This additional assumption states that when the conditions of distribution are changed during the session, the performance level will shift to a level defined by the new conditions of distribution, and the shift curve will be that for a negative exponential function whose rate is given by the value of i associated with the new conditions of distribution. This means that the shift from massed to distributed conditions of practice will be more gradual in rate than the shift from distributed to massed conditions of practice. And further, following the completion of the shift in performance, the relative level of performance attained will be independent of the previous conditions of distribution. It will also mean that the number of trials required to effect a complete shift from one level of performance to a new level of performance will be independent of the number of preceding training trials under the old conditions of distribution. The particular adaptation of Equation 1 for describing performance after a shift in the conditions of distribution has been made, is as follows:

$$P = M - [M - P_x + bT_x][e^{-i(T-T_x)}] + bT, \quad (3)$$

where M and i are values associated with the new conditions of distribution and where P_x and T_x are the values for performance level and trial number, respectively, on the final trial before shift is made. This is essentially the same technique employed by Hull for predicting shift in performance with a change in magnitude of reward (**4**). Hypothetical shift curves for changes from massed to distributed and distributed to massed practice have been determined and are shown in Fig. 1 on the two uppermost curves. The implication that the level of performance following shift in conditions of distribution will be equivalent to the level of performance associated with the new conditions of practice is consistent with data published by Lorge (**5**), Gentry (**3**), and Hilgard and his students (**1, 2**).

Several remarks on the use of Equation 1 seem required. There appear to be two fundamental approaches in the development of a theory that will adequately explain a specified class of behavior phenomena in terms of a limited number of concepts. The first approach is a relatively *ad hoc* programing of a theoretical system and then subjecting deductions from this theory to empirical test. The second approach is one of calculated empiricism. That is, research is not undertaken on a let's-see-what-happens basis, but rather proceeds along the lines of exhaustively investigating the effects of a limited number of variables on behavior. When these empirical relationships become well established, the theorist can then specify concepts and relationships among concepts that will account for the obtained findings. Presumably, a good theory will generate not only statements consistent with known empirical findings but also statements regarding relationships in areas yet to be investigated that will be substantiated upon empirical check.

The use of Equation 1 is in the tradition of this second approach to theory construction. No attempt has been made at specifying theoretical concepts and their interrelation. Instead, Equation 1 is used to state as accurately and as simply as possible the effect of distribution and shift in distribution of practice on the characteristics of psychomotor performance curves within the range investigated.

No effort has been made to have Equation 1 describe performance over all stages of training. It will be noted that Equation 1 does not accommodate asymptotic effects. The presence of the bT term permits P to grow without bound as T increases without limit and this obviously leads to discrepancies as performance levels off at an asymptote. At the present time, it appears profitable to carefully evaluate characteristics of psychomotor performance curves within preasymptotic ranges and relate these characteristics to variation of specified variables. When asymptotic effects become known, Equation 1 can be elaborated. In summary then, Equation 1 is not an attempt at theorizing but rather an attempt to economically describe obtained relationships in motor learning.

Method

Apparatus.—The apparatus employed was a 12-unit Rotary Pursuit Test described elsewhere (6). Trial periods and intertrial rest intervals were automatically presented. Time-on-target scores were recorded in units of .001 min. on Standard Electric timers.

Subjects.—The *Ss* were 2,302 basic airmen trainees drawn from the population available at Lackland Air Force Base.

Procedure.—All groups were given 30 acquisition trials of 30 sec. each. The disks turned and a buzzer sounded for 1.5 sec. before the clocks could be activated. Massed and distributed practice conditions were differentiated on the basis of intertrial rest interval. The intertrial interval was 10 sec. for massed and 30 sec. for distributed practice. Seven initially massed experimental groups (M–D) were shifted to dis-

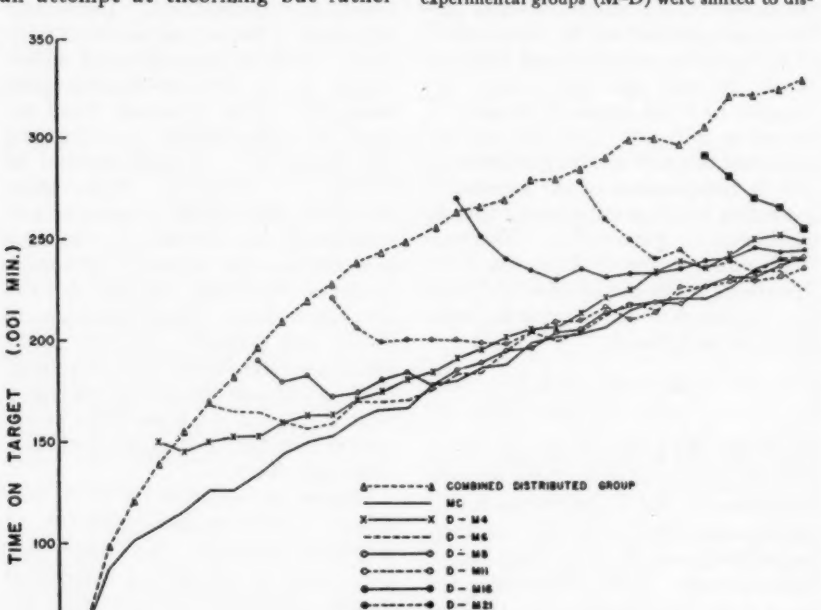

Fig. 2. Performance curves for D–M, MC, and combined distributed groups

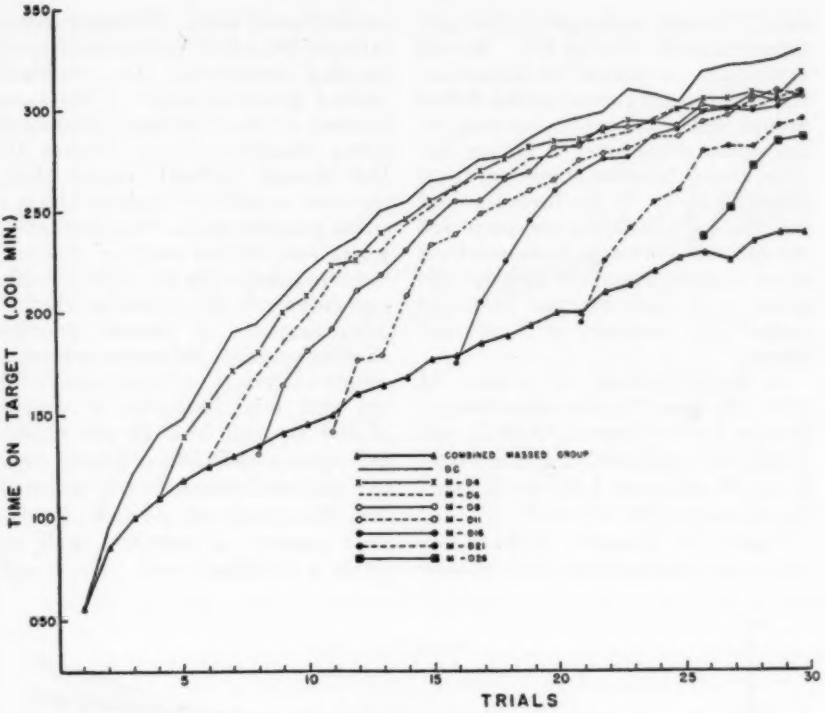

FIG. 3. Performance curves for M–D, DC, and combined distributed groups

tributed practice after 4, 6, 8, 11, 16, 21, and 26 acquisition trials. Seven initially distributed experimental groups (D–M) were shifted to massed practice after the same number of trials. A massed control group (MC) and a distributed control group (DC) had 30 acquisition trials under their respective conditions of practice without shifting. One hundred and forty-four *Ss* were in each group except two which had 143 *Ss* (M–D–11, D–M–6).

RESULTS

The scores for the 16 groups on Trial 1 were subjected to a simple analysis of variance as a test of the hypothesis that they were random samples from the same population prior to differential treatment. The *F* ratio for 15 and 2286 *df* was .74, which permitted retention of the null hypothesis.

The data for the groups which shifted to massed practice following varying numbers of distributed trials are plotted in Fig. 2. The mean of the last preshift trial for each of these groups is indicated on the graph. The lower curve is Group MC which has had massed training throughout. The upper curve is a combined group curve representing performance for all distributed *Ss* up to the point where shift to massed practice occurs. The *N* for the combined distributed group decreases by 143 or 144 *Ss* at each point of shift until 144 *Ss* remain on the last four trials.

It will be noted that with a shift in the conditions of distribution of practice the performance of the experi-

mental groups converges to the performance level of Group MC. As well as this can be judged by inspection, the performance curves for the shifted groups would appear to converge to the performance level of Group MC after about the same number of trials following shift. It has been assumed that Group D-M-26 has not completed the shift to the new performance level so, as a consequence, the data for this group have been omitted from the analysis of variance of final trial scores.

A simple analysis of variance of Trial 30 scores for the experimental Groups D-M-4 through D-M-21 and Group MC was made. For 6 and 1000 *df* the *F* ratio was 1.48, which lacks significance at the 5% level.

Figure 3 presents performance curves for groups shifted from massed to distributed trials. The upper curve is Group DC which has had distributed training throughout. The combined massed group is formed in the same manner as the combined distributed group described above. Groups M-D-6 through M-D-21 require about the same number of trials to attain a stable postshift level. Group M-D-4, which was shifted early in practice, requires fewer trials to attain a stable postshift level. To determine whether prior amounts of massed practice affected postshift performance level, a simple analysis of variance was carried out with Trial 30 scores for groups M-D-4 through M-D-21 and Group DC. Group M-D-26 was deleted from this analysis because it was assumed that this group was given an insufficient number of postshift trials to attain a stabilized level. For 6 and

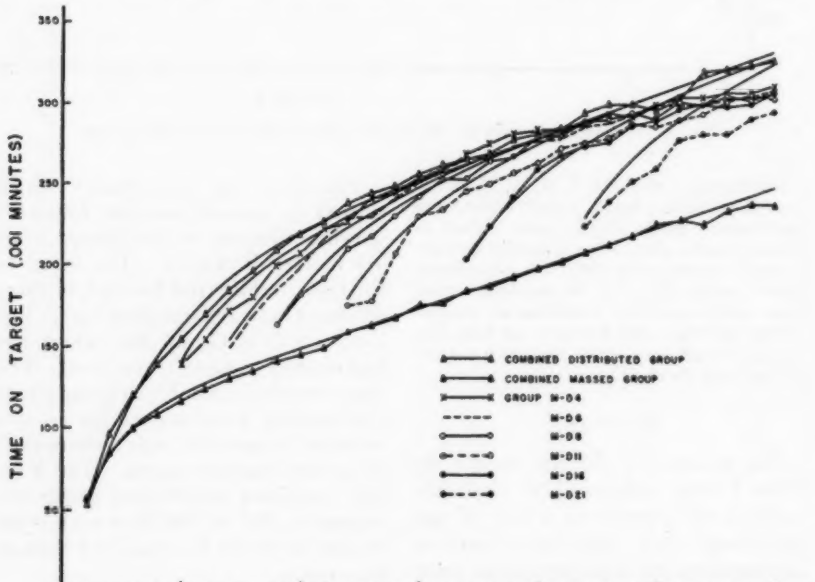

FIG. 4. Fit of hypothesis to the data of the M–D groups

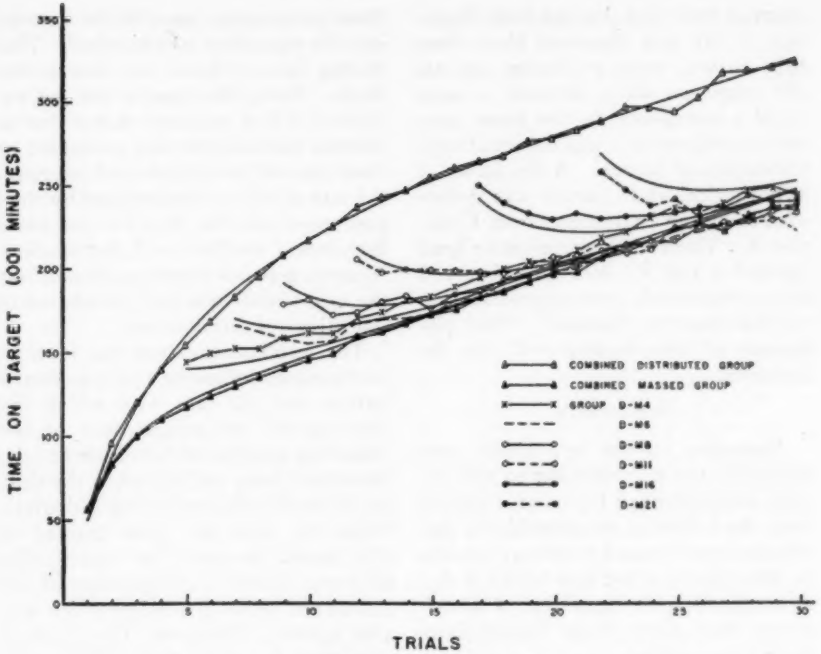

FIG. 5. Fit of hypothesis to the data of the D–M groups

998 *df*, the *F* ratio had a value of 2.59, which is significant between the 1% and 5% levels. The relatively large contribution of Group M-D-21 to between-groups differences on Trial 30 suggested an analysis of variance with this group deleted. For 5 and 855 *df* the *F* ratio had a value of 1.68, which lacks significance at the 5% level of confidence.

Figures 4 and 5 permit an evaluation of the consistency of experimental results with hypothesis. In determining the hypothetical shift curves, values for M and i for the two conditions of distribution were taken from the equations fitted to the combined massed and combined distributed trial means. The two equations thus obtained were

$$P_D = 181(1 - e^{-.25T}) + 5T \quad (4)$$

and

$$P_M = 99(1 - e^{-.67T}) + 5T. \quad (5)$$

The subscripts M and D indicate massed and distributed practice, respectively.

It will be observed that these equations give a very close fit to the empirical data. The hypothetical shift curves shown in Fig. 4 for the shift from massed to distributed trials were derived using values from Equation 4. It will be noted in Fig. 4 that a reasonably close approximation is obtained for all performance curves following shift with the exception of the curve for Group M-D-21. The discrepancy observed for this group will be discussed in a later section.

Hypothetical shift curves for groups shifted from distributed to massed

practice were first derived from Equation 5. It was observed that these shift curves, when evaluated against the empirical data, showed a more rapid convergence to the lower performance level than was observed with the empirical curves. A second set of hypothetical shift curves was generated using the i parameter from Equation 4. These shift curves have been plotted in Fig. 5. It will be observed that a reasonably close approximation to the data is obtained. The sigficance of this finding will also be discussed.

Discussion

According to the hypothesis presented in the introduction to this report, parameters of Equation 1 should bear the following relationship to distributed and massed training: (*a*) $M_D > M_M$; (*b*) $i_D < i_M$; and (*c*) $b_D = b_M$. A comparison of Equations 4 and 5 shows that these three implications have been verified.

A further implication was that equations derived from the over-all performance curves (Equations 4 and 5) would permit derivation of performance curves obtained when *Ss* were shifted from massed to distributed or from distributed to massed practice after varying numbers of trials. In the case of shifts from distributed to massed, the implication has been verified with the single discrepancy that the shift curves did not show a downward trend as steep as the hypothesis would indicate. That is, the i parameter obtained in Equation 5 was too large. Use of the value of i in Equation 4, however, yielded shift curves that were a reasonably close fit to the empirical points. In other words, parameters estimated from the over-all performance data were adequate in deducing the results obtained; a change in the assumption as to how these parameters were to be entered into the equations was required. This finding has at least two interpretations. First, the results can be explained if it is assumed that either in shifting from distributed to massed or from massed to distributed practice, the rate of shift as determined by the i parameter will be that for the more distributed conditions of distribution. A second possible interpretation is that the rate of shift will be independent of conditions of distribution.

The implications that the level of performance following a shift in distribution and the rate with which the shift occurs are independent of the preceding number of distributed trials, have both been verified when the shift was from distributed to massed trials. When the shift was from massed to distributed practice, the assumption that rate of shift is independent of the amount of prior massed practice was also upheld. However, the implication that postshift level following a shift to distributed practice is uninfluenced by the amount of prior massed practice was not entirely substantiated in the present findings. The analysis of variance of Trial 30 scores for Groups M-D-4 through M-D-21 and Group DC yielded an F ratio significant between the 1% and 5% levels. If Group M-D-21 is deleted from this analysis, the F ratio lacks significance at the 5% level. This suggests that Group M-D-21 is stabilizing at a lower mean level than the other groups with a resulting failure to fit the hypothetical shift curve. If this discrepancy between hypothesis and observation is real, then the hypothesis may require expressing M as a joint function of number of trials and intertrial interval rather than intertrial interval alone. There are a number of possibilities with respect to this functional relationship. It may be that, following

the establishment of a relatively stable level of performance associated with a given condition of distribution, there is a slow growth of decremental factors and this growth is only revealed after a relatively large number of trials. An additional problem is the nature of decremental factors contributing to the lower postshift level of Group M-D-21. One possibility is that the observed discrepancies are temporary and would be dissipated if sufficient rest were given at the point of shift. What is required are experiments designed specifically to evaluate these factors.

Summary

The Rotary Pursuit Test was used to investigate the effect of shifting from massed to distributed and from distributed to massed practice after different amounts of training. All groups were given 30 trials of 30-sec. duration. Seven initially massed experimental groups (M–D) were shifted to distributed practice after 4, 6, 8, 11, 16, 21, and 26 trials. Seven initially distributed experimental groups (D–M) were shifted to massed practice after the same number of trials. A massed control group (MC) and a distributed control group (DC) were run under their respective conditions of practice without shifting.

The results were as follows:

1. The D–M groups readily shifted to the level of Group MC and the shift curves for all groups had the same rate.

2. M–D Groups 4–16 readily shifted to the level of Group DC. The performance level of Group M-D-21 was below that of Group DC at the end of the acquisition series. Twenty-one prior massed trials appeared to generate decrement in the postshift distributed trials. The rate of shift curves was generally found to be independent of prior amounts of massed practice.

3. Certain hypothesized relationships on the form of acquisition curves and shift curves were evaluated.

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PERFORMANCE OF AN EFFORTFUL TASK WITH VARIATION IN DURATION OF PRIOR PRACTICE AND ANTICIPATED DURATION OF PRESENT PRACTICE [1]

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Differences in motor performance in line with differences attributable to differential work inhibition have been demonstrated when *S*s merely expect differential work. Ross and Bricker, for example, reported decreases in the strength of a *first* hand-dynamometer pull with increases in the number of pulls to be made (**5**). In the sense that the differences observed are in the same direction as differences between responses following different amounts of prior work or different degrees of distribution of practice, the self-pacing behavior is appropriate to the instructionally set conditions of practice. Related to deliberate attempts to manipulate self-pacing is the problem, discussed by Duncan, of the possible effects of informing *S* of a coming shift in the degree of distribution of practice (**3**).

The cue value of advance instructions concerning the (work) conditions of practice apparently depends on previous experience in the same or similar tasks. A reasonable presumption is that the relevance of prior experience is in the negative aspects of practice associated with massed repetition of responses and the accrual of large amounts of reactive inhibition (I_R)—a negative drive state and decrements in performance output (**4**).

The present study is an attempt to manipulate the effect of the instructional cue to self-pacing by experimental manipulation of *S*'s recent past experience in terms of the duration of prior practice on an effortful task, and therefore, presumably, in terms of the amount of I_R previously accrued on the task. The interaction of two variables was studied: the duration of a first practice period and, after a rest presumably sufficient for complete dissipation of the I_R previously accrued, the instructionally implied duration of a second practice period. A cranking apparatus was used with the expectation that the cranking response would be both effortful enough to assure performance decrement and simple enough to minimize learning effects.

METHOD

Subjects.—The *S*s were 480 naive basic trainee airmen at Lackland Air Force Base.

Apparatus.—The device employed was a manual crank described in greater detail elsewhere (**1**). Substitution of new gears and minor changes in the alignments of drive components increased slightly the horsepower requirements at various rates of rotation, but left the apparatus otherwise unchanged. The apparatus was mounted at the edge of a table with the crank handle projecting outward in the horizontal plane. Turning diameter was 9 in. Force requirements depended on the braking force exerted on the crankshaft by a tachometer generator. Over all possible rates of rotation, the force required to turn the handle was a positively accelerated, increasing function of the rate of response, but the force function was fairly close to linear

[1] The experimental work for this study was performed as part of the United States Air Force Human Resources Research and Development Program. The opinions or conclusions contained in this report are those of the author. They are not to be construed as necessarily reflecting the views or indorsement of the Department of the Air Force.

throughout most of the effective response-rate range. The greatest of five possible work loadings available (Load 4) was used; horsepower requirements at representative rates of rotation were .0432, .0575, and .0745, at 25, 30, and 35 revolutions per 10 sec., respectively.

Two counters on *E*'s control panel, operating in alternate 10-sec. scoring periods, automatically recorded a score of one for each completed revolution of the crank handle.

Design.—The design was a two-variable, 12-cell factorial, utilizing 40 *S*s per cell. The variables were (*a*) duration of initial practice (0 sec., 30 sec., 3 min.), and (*b*) instructionally implied duration of final practice (10 sec., 30 sec., 3 min., 5 min.).

Procedure.—The basic schedule involved an initial continuous practice period of variable duration, a 1-hr. rest, and a final 2-min. period of continuous practice. The *S*s of the four conditions with 0-sec. initial practice, however, actually received only the 2 min. of final practice.

Before initial practice, *S* was told to crank as fast as possible until *E* told him to stop. At the end of initial practice *S* was told how long he had worked and was sent to a waiting room. After the 1-hr. rest *S* was reminded of the duration of his previous practice (if any) and instructed: ". . . I want to see how fast you can turn the crank for 10 sec. (30 sec., 3 min., 5 min.); I will tell you when to stop." Regardless of the duration given in the instructions, however, all *S*s worked for 2 min. in the final period. The number of completed revolutions in successive 10-sec. scoring periods (trials) was recorded.

In both initial and final practice *S* stood squarely in front of the apparatus and turned the crank clockwise. Practice was continuous between starting and stop signals; a ready signal was given 5 sec. before the signal to start.

The total number of cases was reached by adding one *S* per condition for successive, different, testing sequences involving each condition once. The *S*s were assigned to the conditions unsystematically. Except for *S*s with 0-sec. initial practice, all *S*s of a testing sequence had initial practice before the *S* first run returned for final practice. In keeping the 1-hr. rest after 30-sec. or 3-min. initial practice constant, it was found economical to schedule the *S*s with 0-sec. initial practice in about equal proportions to receive their single (final) practice period: (*a*) before the *S*s of the other groups received initial practice; (*b*) during the rest; and (*c*) after final practice was completed by all *S*s who had initial practice.

Results

Initial practice was given only to differentiate between groups on the basis of the amount of decrement incurred in cranking prior to the period in which instructionally implied duration of practice was varied. The relevant findings of initial practice, therefore, are that 30 sec. of practice were sufficient to produce some decrement in performance but not as great a decrement as was incurred in 3 min. In the first 10 sec. of initial practice the grand mean ($N = 160$) of conditions with 30-sec. practice was 40.8 revolutions; in the last 10 sec. the mean was 31.8 revolutions. The grand means of Trials 1 and 18 of the conditions with 3-min. initial practice were 40.4 and 24.7 revolutions per 10 sec., respectively.

In the following sections the data of final practice, only, are considered.[2] The several conditions are identified according to double-classification cell-entry convention—the first number (0, 30, 3) referring to initial-practice treatment, the second (10, 30, 3, 5) to final-practice treatment. Condition 3–10 thus refers to the combination of 3-min. initial practice and 10-sec. (instructionally implied) final practice.

Performance on Trial 1 of final practice.—The mean numbers of revolutions in the first trial of final practice are presented in Fig. 1. Instructionally implied duration of final practice in sec. is the variable, duration of initial practice the parameter. Each point represents the Trial 1 performance of an independent condition ($N = 40$).

Figure 1 shows that, after any duration of initial practice, the rate of

[2] To save printing costs a 5-page table giving the means and variances of each condition for each trial of initial and final practice has been deposited with the American Documentation Institute. Order Document No. 4028 from Chief, Photoduplication Service, ADI Auxiliary Publications Project, c/o Library of Congress, Washington 25, D. C., remitting $1.25 for 35 mm. microfilm or $1.25 for 6 by 8-in. photocopies.

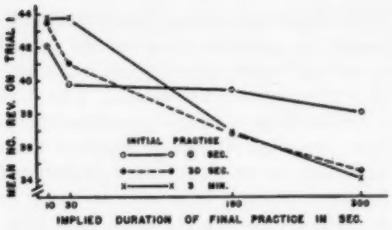

FIG. 1. Rate of response on the first trial of final practice as a function of instructionally implied duration of practice

responding at the start of final practice is lower, the longer the instructionally implied duration of practice. The general trend of the three curves is downward from 10-sec. to 5-min. (300 sec. in Fig. 1) implied duration of practice. The response rate of Cond. 0–10 exceeds the rate of Cond. 0–5; the response rates of the other two 0-sec. initial-practice conditions are appropriately placed between the two extremes. The 30-sec. initial-practice conditions show consistent decreases in starting rate of responding between Cond. 30–10 and 30–5, with no inversions. The 3-min. initial-practice conditions show no inversions as instructionally implied duration of final practice increases from 10 sec. to 5 min., although Cond. 3–10 and 3–30 have identical starting rates of response.

Differences attributable to the duration of initial practice are also evident in Fig. 1. Although all three curves show decreasing rates of response as the implied duration of final practice increases, the negative slope of the curve based on conditions with 0-sec. initial practice is slight, relative to the over-all slopes of the 30-sec. and 3-min. curves. The longer the duration of initial practice, the more marked the effect on starting rate of response of variation in the implied duration of final practice. The difference between the means of: (*a*) 3–10 and 3–5 is 9.7; (*b*) 30–10 and 30–5 is 9.0; and (*c*) 0–10 and 0–5 is 4.0. This interaction of the experimental variables is evident in Fig. 1 in the crossing of the three curves. When brief durations (10 or 30 sec.) of practice are implied, response rate on Trial 1 of final practice is higher the longer the duration of initial practice. When relatively long durations (3 or 5 min.) are implied, the response rate at the start of final practice is highest after 0-sec. initial practice.

In a two-way analysis of variance of the data of Trial 1, the interaction mean square (147.61, $df = 6$) and the mean square for the implied duration-of-practice main effect (1441.28, $df = 3$) were significant beyond the 1% level of confidence, evaluated by the within-groups error term (18.63, $df = 468$). The mean square for the initial-practice main effect (35.41, $df = 2$) was not significant at even the 5% level of confidence. In spite of differences between conditions at each implied duration of practice, the interaction for the values used in the present study results in almost equal grand means for the different durations of initial practice. In comparisons of individual conditions, mean differences of 2 and 2.5 revolutions, respectively, approximate the 5% and 1% levels of confidence.

Comparisons of conditions at successive values of the final-practice variable indicate that the major effect of initial practice is to separate conditions with 0-sec. initial practice from conditions with some initial practice. As the implied duration of final practice increases, the differences between conditions with 30-sec. and 3-min. initial practice show a trend similar to the trend of differences between conditions with 0-sec. and conditions with 30-sec. or 3-min. initial practice.

That is, when the implied duration of final practice is brief, response rate is higher after 3-min. initial practice, while at the longest implied duration the ranks of 30-sec. and 3-min. conditions are reversed. However, only when the implied duration of final practice is 30 sec. (30–30 vs. 3–30), is there any sizable difference between conditions with 30-sec. and 3-min. initial practice; when the implied duration is 3 min. or 5 min., the difference is negligible. Initial practice thus has an effect on performance, as some initial practice vs. none, but the two different durations of initial practice have only slightly different effects.[3]

Decrement as a function of starting rate.—While performance on Trial 1 was depressed with increasing implied durations of practice, the self-pacing apparent in starting rates was not such as to eliminate decrement in output as final practice continued. Work decrement was evident in each condition, though the amount of decrement was less, in general, the lower the starting rate. The rapid occurrence of decrement and the relation of decrement to starting rate are illustrated in Fig. 2. The mean difference between numbers of revolutions in Trials 1 and 2 is plotted for each of the twelve conditions against mean number of revolutions on Trial 1. Straight-line segments connect conditions with the same duration of initial practice. Since Cond. 3–10 and 3–30 had equal starting rates and unequal decrements, the curve has been passed midway between—below 3–10 and above 3–30; otherwise, from left to right within each curve, successive entries are based on conditions with decreasing implied durations of final practice.

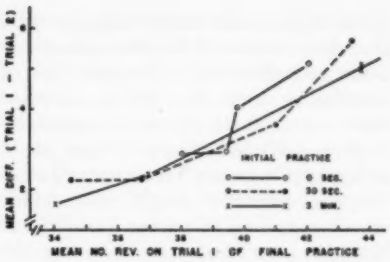

FIG. 2. Difference between the numbers of revolutions in the first and second 10-sec. trials of final practice as a function of the number of revolutions in the first trial

Duration of initial practice constant, the mean difference between Trials 1 and 2 is clearly an increasing function of the mean rate of response on Trial 1. With initial practice variable several reversals are evident between conditions with relatively high starting rates.

The presentation in Fig. 2 confounds two possible sources of differential decrement in the different treatments administered to the conditions: the decrement attributable to the treatment effect on Trial 1, and any differential decremental effect specific to a given treatment. In order to partial out this confounding, the *Ss* of each condition were divided into quartiles ($N = 10$) on the basis of rate of responding on Trial 1, and the mean starting rate and mean difference between Trials 1 and 2 were computed for each quartile. The between-condition overlap in starting rates thus provided a basis, independent of the

[3] To check the question of the effect of variation in duration of initial practice an additional 120 *Ss* were run in a six-cell factorial in which initial practice took the values 10 sec. and 30 sec. and final practice the values 10 sec., 30 sec., and 5 min. Mean numbers of revolutions in the first trial of final practice were 43.0, 41.6, and 35.3 for Cond. 30–10, 30–30, and 30–5, respectively, and 42.3, 42.0, and 37.6 for Cond. 10–10, 10–30, and 10–5. The trend of the differences between 10-sec. and 30-sec. initial-practice conditions as implied duration increased was thus roughly in line with trends in the present data. Again, however, differences attributable to duration of initial practice were small.

Trial 1 effect, for comparing the relative decrements of the various conditions. Consistently, the quartiles of conditions with the 10-sec. implied duration of final practice (especially 0–10 and 30–10) showed larger mean differences between Trials 1 and 2 than did the quartiles (with comparable starting rates) of other conditions. No other consistent trend between the twelve conditions was evident in inspectional comparisons of conditions with respect to either variable. The slight over-all positive acceleration of decrement as a function of starting rate in Fig. 2 may thus depend largely on the excessive decrement of conditions with the 10-sec. implied duration of final practice, although the differential decrements appear primarily attributable to differential starting rates.

Performance throughout final practice.—Mean numbers of revolutions in successive trials of the 2 min. of continuous final practice are shown in Fig. 3. Three sets of curves are presented, plotted against the same ordinate but with separate abscissas. The sets of curves represent, from left to right, conditions with 0-sec., 30-sec., and 3-min. initial practice, with implied duration of final practice the parameter in each set of curves. The curves of the twelve conditions show a common trend for progressive, negatively accelerated decreases in rate of responding as a function of trials.

The early severe expenditure of energy with implied durations of 10 sec. and 30 sec., relative to the conservation evident with implied durations of 3 min. and 5 min., might be expected to result in a shift in rank ordering of the conditions in later trials, as well as in the differential decrement evident between Trials 1 and 2. A complete reversal of the

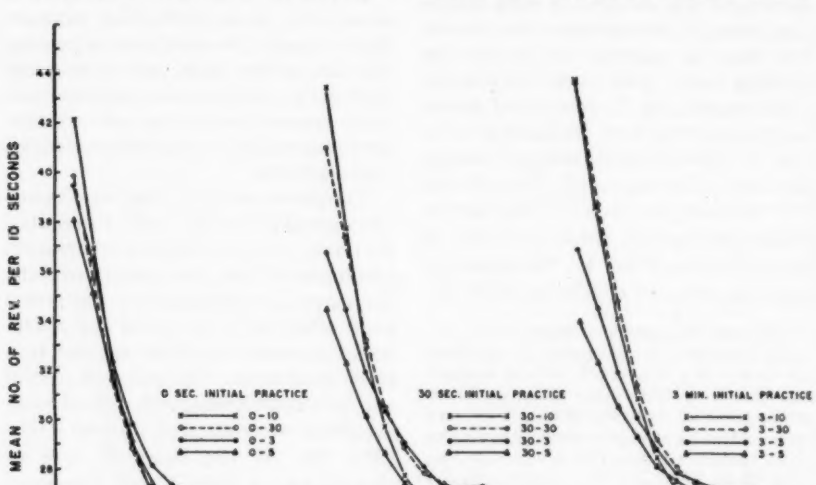

FIG. 3. Rate of response in successive 10-sec. trials of final practice

Trial 1 rank ordering is not an unreasonable expectation, even within the 2 min. of practice given. Each set of curves in Fig. 3 does show further decreases between conditions after Trial 2, and while no complete reversal of relative rankings takes place, the curves, in general, converge and in each set the curves of most of the conditions cross before the end of final practice. Comparison of the general trends of the three sets of curves suggests that the most consistent tendency between sets is toward increasing delay in the trial at which (roughly) the curves can be said to converge. Thus, for each duration of initial practice, the curve of the condition with 10-sec. implied duration of final practice crosses (or reaches the same level as) the curve of every condition with a longer implied duration of final practice, while the curves of conditions with 30-sec. and 3-min. implied durations also converge and cross. In their respective sets of curves in Fig. 3, Cond. 0–5, 30–5, and 3–5 may be observed as the only exceptions to a general phenomenon in which the curve of each condition, at some point in final practice, crosses the curve of every condition with a briefer implied duration of practice.

It is apparent in Fig. 3, however, that differences between conditions with the same duration of initial practice are, in general, greatest on Trial 1, and relatively slight in the terminal trials. In a two-way analysis of variance of the Trial 12 data, the F ratio of the mean square for implied duration of practice (22.25, $df = 3$) to the within-groups error estimate (6.79, $df = 468$) was significant at better than the 5% level of confidence. By and large, comparisons of conditions with duration of initial practice variable and implied duration of final practice constant, also reveal lesser differences between terminal rates of responding than between starting rates. Response rate in the terminal trials was, in general, positively related to duration of initial practice, but neither the initial-practice main effect nor the interaction mean square reached the 5% level of confidence in the Trial 12 analysis of variance. In the present experiment, at least, the largest and most clear-cut differences attributable to either variable appear to be associated with the earliest portion of final practice.

Discussion

Differences in rate of cranking in the first 10 sec. of final practice occurred with variation in either experimental variable—duration of initial practice or instructionally implied duration of final practice. Both variables may be described as having effects appropriate to the inhibitory effects of actual long durations of practice; performance was progressively depressed by increases in the implied duration of present practice, and, at long implied durations of final practice, by increasing previous work experience. In other words, the self-pacing or conservation behavior for both experimental manipulations is consistent with the implications of Hull's conditioned inhibition ($_sI_R$) construct (4). Thus, differences with different implied durations of final practice may be interpreted in terms of the differential activation of an acquired inhibitory tendency; at long implied durations of final practice differences between conditions with different durations of initial practice may be interpreted in terms of the activation of inhibitory tendencies of different magnitudes.

The positive relation of performance to duration of initial practice at brief implied durations of final practice may

be attributable to learning or may represent a contrast effect; the positive relationship at least suggests that the rest between initial and final practice was adequate for the dissipation of the temporary work inhibition accrued in initial practice. If learning or response strengthening did take place in the present study, the strengthening would serve to mask the negative effects of initial practice at long implied durations of final practice. It should be pointed out that in a previous study with the same apparatus, starting rate (revolutions per 20 sec.) failed to indicate any learning over ten days of practice (**2**).

Performance throughout final practice.—Major emphasis has been placed on performance in the first trial of final practice because of the presumed greater complexity of the determinants of performance in later trials. On the first trial the effects of the two variables are relatively unconfounded with the effects of secondary performance determinants. Later differences in performance, however, duration of initial practice constant, might depend on: (*a*) differential I_R attributable to differences in starting rate, (*b*) continued depression of performance in conditions with implied durations of practice longer than the 2 min. actually given, and (*c*) changes in motivation as practice continues beyond the expected time, in conditions with brief implied durations of practice.

Decrement between Trials 1 and 2 of final practice, as a function of *a* and/or *c* above, was clearly a positive function of starting rate, a finding in agreement with previous analyses of decrements in the top and bottom quartiles of a single group (**1**). The finding is in agreement also, of course, with the within-groups negative acceleration in decrement as a function of trials—the largest decrements within groups occur at high response rates; at low response rates decrements from trial to trial are negligible.

Continued differential decrement, other things equal, would be expected to lead in later trials to reversal in the ranks of any pair of conditions with different starting rates; if in later trials of final practice I_R alone varies, then the condition with the greater number of responses in preceding trials, and the greater I_R, should exhibit the lower rate of responding. As final practice progressed there was considerable alteration in the relative rankings of conditions with different implied durations of practice, duration of initial practice constant, though differences between groups in later trials were not comparable in magnitude to the differences on Trial 1. That for each value of initial practice, the condition with the longest implied duration of final practice did not exhibit complete convergence may indicate continued, severe pacing for the longest implied duration of practice. A longer final-practice period would be required to test the expectation that the effect of initial conservation at long implied durations of practice is evident in greater output in later trials.

Summary

Four hundred and eighty basic trainee airmen served as *S*s in an experiment varying the duration of an initial-practice period on a cranking apparatus and the instructionally implied duration of a final period of 2-min. continuous practice. In general, differences attributable to either variable were greatest on the first 10-sec. trial of final practice. Rate of response on Trial 1 of final practice decreased with increasing instructionally implied duration of practice, for any duration

of initial practice, though the variables interacted such that the relationship of performance to initial practice varied with the implied duration of final practice. Decrement between Trials 1 and 2 of final practice was positively related to starting rate of response, and as final practice continued, the curves of conditions with different implied durations showed some tendency toward a reversal of the Trial 1 ranking.

The self-pacing behavior evident in the early portion of final practice was interpreted in terms of Hull's conditioned inhibition, while later behavior was considered as reflecting the increased influence of reactive inhibition.

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TEMPORAL FACTORS INFLUENCING THE PERCEPTION OF VISUAL FLICKER [1]

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While the spatial (**3, 6, 7, 13, 18, 22**), spectral (**10, 12, 16**), and intensity (**4, 8, 9, 16, 18**) dimensions of light have been thoroughly investigated in experiments on critical flicker frequency (CFF), the temporal dimension has not been systematically explored. Studies have indicated that prolonged inspection decreases the fusion frequency (**6, 14**), and that CFF is also changed when the relative duration of the light and dark phases within each cycle (the light-dark ratio) is altered (**9, 10, 23, 24**). No agreement exists, however, as to the amount and direction of these changes in CFF when the light-dark ratio is systematically varied over a wide range (**2**). Presumably, these disparate results reflect the type of procedure used, such as manipulating the flash intensity in order to maintain a constant "Talbot level of brightness"[3] (**23, 24**).

It is important to study the temporal dimension in CFF, particularly in the case of very brief exposures of an intermittent test patch. It is clear, for example, that the perception of flicker would be impossible if the period of observation (the exposure time of the test patch) were the same as, or less than, the duration of a single light flash in the intermittent cycle. Apart from such purely physical limitations, however, the question arises as to whether CFF changes systematically as the duration of test-patch exposure is shortened. The present experiment was designed primarily to answer this question. As a secondary goal we attempted to relate CFF to the light-dark ratio under conditions of constant flash intensity.

METHOD

Subjects.—The authors served alternately as *Os* and *Es*. One *O* (WB) had normal color vision (as tested on pseudoisochromatic plates) but was myopic (Snellen acuity O.D. 20/80, O.S. 20/100). The other *O* (RJ) showed some impairment in red-green discrimination but had normal acuity (O.D. 20/20, O.S. 20/20). Both *Os* were experienced in making visual discriminations; their visual fields were full for a 1° white target, and the fundi were normal upon ophthalmoscopic examination.

Apparatus.—Some of the details of the apparatus have been given in a previous publication (**3**). A variable-frequency "square" wave generator (rise and fall time .5% of the period) was used to power a gas discharge tube (Sylvania No. R1130B). The frequency output of the generator was continuously variable from 1 to 60 cps (± .1 cps). The relative duration of the light and dark phases within each cycle, i.e., the percentage of the period occupied by light, was also independently variable from 0% (all dark) to 100% (all light) with an accuracy in the intermediate range of ± 1%. In order to control the

[1] This work was carried out as part of a larger project under Contract No. V1001M-176 with the United States Veterans Administration. The authors are indebted to Drs. M. B. Bender and H. L. Teuber for their helpful comments during the course of the study.

[2] This work was done when both authors were at the Department of Neurology, New York University College of Medicine. While the study was in progress, R. Jaffe was working under a postdoctorate fellowship of the United States Public Health Service.

[3] According to Talbot's law, the "effective" intensity of an intermittent light is equal to the flash intensity multiplied by the percentage of the cycle duration occupied by light (**15**). This equation holds exactly for calculations of energy content; moreover, it is a valid estimate of brightness at and above fusion (**1**). When flash intensity is altered in order to maintain a constant "Talbot level" of light intensity, however, differences in brightness then occur *below* fusion (**1**).

over-all duration of the intermittent light an electronic timer was used. This timer activated a high-speed magnetic relay interposed in the generator-to-gas discharge-tube circuit. Initially, the output of the generator was led to a dummy load. When *O* pressed a break-circuit microswitch, the generator output was transferred from the dummy load to the gas discharge tube via the relay; this circuit was then maintained for any duration preset on the timer (± 1 msec.).

The gas discharge tube was mounted on a carrier attached to a Brombach perimeter. Light from the tube passed through a circular target disc and formed an image in the plane of an opal glass test plate. The target disc was 13.9 mm. in diameter, subtending 2°52′ of visual angle at the viewing distance used (277 mm.). No diffraction or aberration of the test patch was noticed by *Os*.

By means of a photocell pickup and cathode ray oscillograph, the light output of the gas discharge tube was calibrated with respect to frequency, percentage of period occupied by light, wave form, synchronization, and over-all duration of exposure.[4] The flash intensity of the test patch, as measured with a Macbeth illuminometer, was 10.9 candles per sq. ft. Spectral emission, relative to a standard tungsten filament, was measured with a Koenig-Martins spectrophotometer. A "line" spectrum which covered the range of visible wavelengths but which had a major mode in the vicinity of 5,850A° was found.

Since all experiments were conducted in a completely dark room, it was necessary to provide *O* with a fixation spot. This was accomplished by painting four index marks around the circular-target disc with blue-white phosphorescent paint. The *O* saw four dim marks at 12, 3, 6, and 9 o'clock, and could easily fixate the center of this "clock" target when anticipating the presentation of the test patch. The intensity of the test patch prevented *O* from seeing the fixation marks during the exposure periods.

Procedure.—In any one testing session *O* was dark adapted for about 10 min., or until he could clearly see the test patch. The *E* meanwhile set the relative duration of the light phase at either 20%, 50% or 80% of cycle duration; the over-all duration of exposure of the test patch was also fixed at one of the following values: 140, 160, 180, 200, 250, 300, 350, 400, 500, 750 or 1000 msec. (The *O* was never told the value of these two parameters.) Using only the dominant eye, *O* fixated the center of the target "clock" and exposed the test patch at his own discretion by pressing the microswitch. He judged the light as either "flickering" or "not flickering," and continued to expose the test patch at approximately 2-sec. intervals until stopped by *E*.

The *E* initially set the frequency output at a low value so that *O* readily saw "coarse" flicker. In successive exposures the frequency was then increased, rapidly at first, later in increments of .2 cps until *O* reported "not flickering." This procedure was then reversed by setting the frequency well above fusion and decreasing it in the same manner until reports of "flickering" were elicited. In each trial, whether in ascending or descending order, one or more "blanks" were inserted. That is, *E* abruptly changed the frequency well above or below the fusion point to make certain that *O* was not responding to extraneous factors. After two ascending and two descending readings were taken to establish the rough limits of "flicker" and "no flicker," 20 alternate ascending and descending test trials were made to determine the precise frequencies which corresponded to the disappearance and reappearance of subjective flicker. The median cyclic rate between each of the ten pairs of ascending and descending frequencies was taken as an estimate of the fusion threshold (CFF), and the mean and standard deviation of the distribution of these medians calculated. In succeeding sessions this procedure was repeated in random order for the 33 combinations of the two main independent variables—percentage of period occupied by the light phase and exposure time.

At extremely short durations of exposure both *Os* experienced difficulty in obtaining reliable estimates of the fusion frequency. In part, this was due to limitations in instrumentation (cf. footnote 4). In order to extend the data over as wide a range as possible, however, the dependent and independent variables were interchanged at these short intervals. Specifically, the frequency output was fixed at either 6, 10, 14, or 18 cps, and the over-all exposure time alternately increased and decreased until flicker or fusion was reported. Since it was very difficult to get good subjective end points at these short exposures, the results are less reliable than those at longer intervals; the importance of the data at

[4] The authors are grateful to Drs. P. S. Bergman and M. Nathanson for their help in calibrating the apparatus. It was noted during calibration that the start of the exposure interval could occur at any time during a cycle of intermittence. This was due to the fact that the circuits used did not provide any means of synchronizing ("gating") the onset of the exposure interval with the rising wave front of the first light pulse in the intermittent cycle. The exact effect of this deficiency in instrumentation is unknown, but both *Os* found it difficult to maintain reliable criteria of fusion or flicker at extremely short exposure intervals.

TABLE 1

MEANS AND *SD*'S OF FUSION THRESHOLDS (IN CPS) AT DIFFERENT COMBINATIONS OF EXPOSURE TIME AND LIGHT–DARK RATIO*

Exposure Time in Milliseconds	Observer WSB						Observer RJ					
	Light-Dark Ratio						Light-Dark Ratio					
	20%		50%		80%		20%		50%		80%	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
140	21.7	.8	15.8	.6	**		14.0	.5	**		**	
160	23.8	.7	21.8	.8	**		22.3	.6	20.8	.8	**	
180	29.4	.5	27.3	.2	21.8	.9	29.0	.4	25.7	.6	**	
200	31.3	.4	32.2	.9	19.8	.7	27.7	.5	29.6	.6	18.4	.8
250	34.3	.4	36.1	.8	26.5	.2	29.8	.2	34.6	.4	24.3	1.0
300	34.4	.3	37.3	.2	26.1	.4	33.3	.6	35.1	.4	31.0	.5
350	38.0	.2	38.1	.2	31.0	.7	33.2	.3	36.2	.3	33.4	.2
400	35.2	.1	37.0	.2	32.7	1.1	35.4	.3	37.0	.4	34.4	.4
500	38.5	.2	39.5	.1	33.7	.2	37.0	.4	40.0	.4	33.0	.5
750	38.6	.1	40.9	.2	36.2	.3	38.4	.3	40.5	.2	35.0	.3
1000	38.4	.2	41.1	.2	36.4	.2	37.7	.4	39.2	.5	36.6	.6

* All calculations are based on ten median thresholds of flicker fusion per combination. Each median obtained from alternating "ascending" and "descending" readings.
** Reliable measurements impossible.

extremely short intervals is not stressed in this paper.

In all the procedures so far described, the relative light time was held constant at one of three values (20%, 50%, or 80% of the period). As a further check on the importance of this parameter, *O*'s responses were noted when the relative light time was directly varied at the empirically determined frequency for any given exposure interval.

RESULTS

Table 1 presents the mean CFF's and their *SD*'s for both *O*s. Table 2 gives the mean exposure times, and their *SD*'s, at extremely short exposure intervals and low rates of intermittence. Adhering to the conventional method of graphing flicker-fusion data, Fig. 1 shows CFF plotted along the ordinate in cycles per second, and duration of exposure along the abscissa in milliseconds. Curves are given for the 20%, 50%, and 80% light periods for each *O*. At short durations of exposure solid symbols are shown. These symbols refer to the less reliable mean exposure time at the flicker-fusion threshold (the values obtained by holding frequency of intermittence constant and varying only the duration of exposure). The other open symbols show the mean frequency at the fusion threshold, obtained by holding exposure time constant and varying the rate of intermittence. The freehand curves drawn through these thresholds indicate a rising function, of negatively accelerated slope, for each of the three light-dark ratios.[5]

[5] The function obtained with 20% relative light time tends to change slope at lower rates of intermittence; i.e., mean exposure time tends to increase as cyclic rate decreases. Theoretically, as the rate of light intermittence approaches zero, exposure time should approach infinity in order to include at least one complete cycle of intermittence within the exposure interval. Over the higher range of exposure times and cyclic rates employed, however, the functions can be adequately described as negatively accelerated and rising. The possibility exists that the results obtained at extremely short durations of exposure are different in character from the remainder of the data.

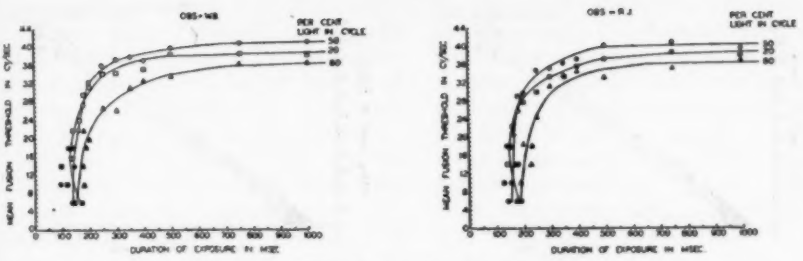

FIG. 1. CFF as a function of exposure time

The slopes and asymptotic values of the functions shown in Fig. 1 vary, depending upon the percentage of light in the cycle. With a high percentage of light (80% of cycle duration), the slope and asymptote are smaller than those obtained with less light percentages. On the other hand, the steepest slope and highest asymptote were obtained when the light and dark phases were of equal duration (50% light); intermediate values resulted with low relative light durations (20% light). These findings were empirically confirmed by directly varying the proportion of light in the cycle when the frequency and exposure time were set at previously determined critical levels for fusion. Under these circumstances the *O*s' estimates of "flicker" or "no flicker" were in accord with the curves shown in the figure.

In general, the raw data indicate that fusion frequency is a negatively accelerated, rising function of exposure time. At any one duration of exposure, however, the product of the fusion frequency (in cycles per second) and the exposure time (in seconds) results in a statistic which represents the maximal *number* of successive light flashes which *O* could perceive as flickering. We have called this statistic the critical number of flashes. Figure 2 shows how the raw data for both *O*s are affected by replotting in terms of critical number of flashes on the ordinate and exposure time on the abscissa. The curve for each of the

TABLE 2

MEANS AND *SD*'S OF CRITICAL EXPOSURE TIMES (IN MILLISECONDS) AT THE FUSION THRESHOLD, FOR COMBINATIONS OF FREQUENCY AND LIGHT–DARK RATIO*

Frequency in CPS	Observer WSB						Observer RJ					
	Light-Dark Ratio						Light-Dark Ratio					
	20%		50%		80%		20%		50%		80%	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
6	169	3.0	139	1.7	140	.8	185	2.2	139	2.1	172	3.0
10	114	6.5	93	2.1	178	1.3	127	2.1	152	.3	187	1.3
14	95	1.3	145	.9	175	2.0	168	1.4	173	.8	228	4.4
18	138	3.5	123	3.6	191	1.3	148	.4	139	2.1	233	6.1

* All calculations based on five median thresholds of flicker fusion per combination. Each median obtained from alternate "ascending" and "descending" pairs of exposure-time measurements.

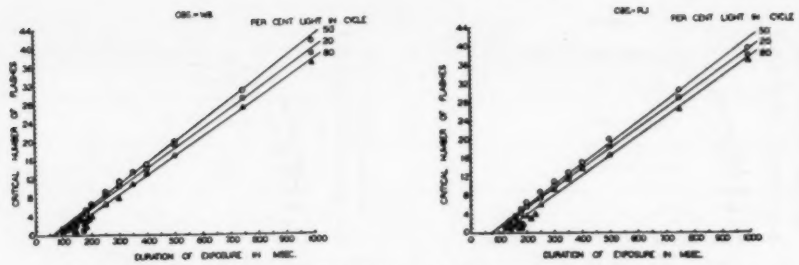

FIG. 2. Number of successive light flashes at fusion as a function of exposure time

three light percentages becomes linear. The slopes of these straight-line functions demonstrate that the critical *number* of flashes per *unit* time is constant at fusion. Therefore, although CFF changes systematically with the exposure interval, the fusion threshold, expressed in terms of flashes per *unit* time, remains relatively constant.

Aside from linearity, the most striking aspect of the curves in Fig. 2 is the fact that they lie so close together, despite the quite different energy contents they represent. Since the total light energy in a train of flashes is directly proportional to the percentage of the period occupied by the light phase, the curves in Fig. 2 can be equated for energy content by multiplying the flash intensity by the light-dark ratio (Talbot's law). If this product is further multiplied by the exposure time and the target area, an estimate of energy content in candle-milliseconds is obtained.

Figure 3 indicates how the slopes of the three light-percentage curves are altered when the data are replotted in terms of critical number of flashes on the ordinate, and light energy, in candle-milliseconds, on the abscissa. These curves are now equated for energy content; therefore, the relative duration of the light and dark phases (percentage of period occupied by light) is the *only* factor determining differences in the slopes of these functions. Inspection of these slopes shows that the smaller the percentage of light, the greater the *number* of flashes per unit energy which can be individually discriminated.

DISCUSSION

"Excitation" and "recovery" in the visual system.—It is generally assumed

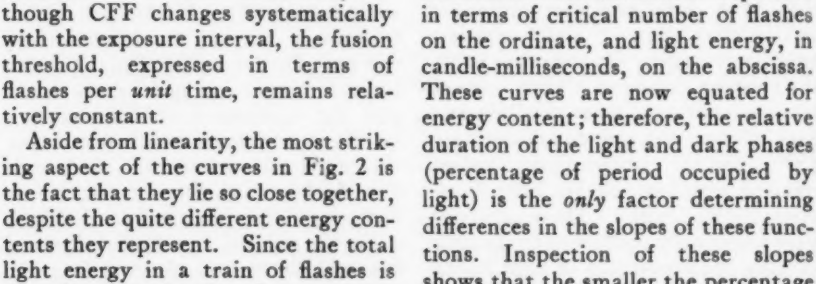

FIG. 3. Number of successive light flashes at fusion as a function of total energy content

that each successive flash of an intermittent light "excites" the visual system, leaving residual effects which disappear mainly during the dark phase (**2, 11, 19, 20, 23**). According to this point of view, the ability to perceive successive stimuli as discrete (the temporal resolving power of the visual system), depends upon the amount of "excitation" produced by the light, and the time needed for "recovery" from the residual effects.

Confirming previous investigations (**2, 23**), the raw data presented in Fig. 1 indicate that the greatest gain in CFF (the slope of the CFF–exposure-time function), and the maximum CFF value, was obtained when the light occupied 50% of the cycle duration. In terms of the concepts outlined above, this finding means that equal durations of the light and dark phases provide the optimal balance between "excitation" due to light stimulation, and time needed for "recovery" from residual effects. The straight-line curves in Fig. 2 indicate that this balance between "excitation" and "recovery" proceeds at a relatively constant rate irrespective of the duration of observation. To what extent the effects observed depend upon such factors as flash intensity (**2, 9**) is unknown, since this parameter was not varied in the present study.

Effects of total light energy on temporal resolution.—The results in Fig. 3 showed a linear function between the critical number of flashes at fusion and aggregate light energy; a function whose slope varied inversely with the percentage of light time. In other words, when periods of stimulation contained the same amount of aggregate light energy, and differed only in the relative duration of the light and dark phases, the shorter the relative light phase (or conversely, the longer the relative dark phase) the greater the number of light flashes which could be perceived as discrete entities. These findings can be interpreted as showing that the factors mediating the perception of flicker operate most efficiently (in terms of recovery from previous stimulation) as the relative dark period increases in duration. This conclusion agrees with previous findings (**23, 24**), where the CFF's obtained with flash intensity held constant were compared with those resulting when flash intensity was varied according to Talbot's law.

Physiological bases for flicker perception.—This study cannot define the structures in the visual system which function as the limiting factors in the perception of flicker. Our results can be briefly discussed, however, with regard to existent physiological theories of visual function.

Hecht and his co-workers have attributed the limiting factor in flicker fusion to the balance between the breakdown and resynthesis of photosensitive substance in the retinal receptors during the light and dark phases of the stimulating cycle (**18, 19, 20**). Specifically, a pseudo-steady state is assumed to exist at fusion: a state in which changes in the concentration of photosensitive substance are too small to produce any subjective effect; i.e., no change in "photochemical effect" is produced at fusion. According to this theory, increasing the relative dark interval of an intermittent light should result in a greater amount of photosensitive substance resynthesized and hence greater sensitivity to subsequent stimulation. Since these were the effects obtained in the present experiment, one can say that our results are compatible with photochemical theory. However, the same results could have been predicted from quite a different point of view.

Crozier and his collaborators have stressed the importance of neural mechanisms in the phenomenon of fusion (**8, 9, 11, 12**). This viewpoint assumes a random distribution of thresholds in the neurons of the visual system. At any one flash intensity, a certain number of these neurons will be stimulated (depending upon their thresholds), and will vary in their recovery from this stimulation according to their refractory periods. At the fusion point, the number of neurons entering the excitatory state equals the number recovering from previous stimulation; hence, there is no change in "neural effect" and fusion occurs. In terms of this theory, the longer the dark interval in a train of light flashes, the greater the number of neurons which could recover from their refractory state and become "available" for further stimulation. It follows, therefore, that *O*'s ability to discriminate between successive flashes would increase correspondingly.

Thus, although our results agree, in general, with the concepts of "excitation" and "recovery" in the visual system, they do not permit us to draw any conclusion regarding the structural factors determining fusion. Apparently, one cannot conclude that the failure in temporal resolution which characterizes fusion is due to a lack of either a photochemical or a neural "effect," without attempting directly to manipulate the relevant variables (**3, 4, 5, 25**). The present results appear equally predictable from either neural or photochemical theory. Further studies, wherein quantal energy content is considered, may aid in the further elucidation of the phenomena reported.

Summary and Conclusions

A study of the temporal factors influencing CFF was performed. Using a "square" wave stimulator, an electronic interval timer, and a gas discharge tube, measures of CFF were taken from two *O*s when the over-all duration of exposure of the intermittent light was varied from 140 to 1000 msec. for each of three relative light percentages (light-dark ratios). For both *O*s, the plot of CFF vs. exposure time was a rising function of negatively accelerated slope. The magnitude of the slope of these functions varied with the percentage of the period occupied by light (in the order 50%, 20%, 80%). When the data were replotted in terms of *number* of light flashes at fusion vs. exposure time (as contrasted to *frequency* of flashes, or CFF, vs. exposure time), a linear curve for each light-dark ratio was found. These findings indicate that CFF, expressed in cps, varies systematically as exposure time is shortened, but that the *number* of flashes per *unit* time is relatively constant at fusion.

When the raw data obtained with each light-dark ratio were equated for total energy content, it was found that the longer the relative dark interval in an intermittent light cycle, the greater the ability of *O* to discriminate between successive flashes. These results are compatible with concepts of "excitation" and "recovery" in the visual system, but are equally predictable from either neural or photochemical theory. It is suggested that the relative merits of these theories can only be appraised in experiments where neural or photochemical factors are directly manipulated.

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PRIMARY OCULAR NYSTAGMUS AS A FUNCTION OF INTENSITY AND DURATION OF ACCELERATION[1]

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The present study concerns the extent and duration of eye movements resulting from rotation of widely varying speeds and accelerations and photographically recorded through closed lids at high magnification. The results are expected to add to the basic data necessary for construction of a theory concerning the mode of action of the peripheral vestibular apparatus and its central components. Previous investigations have indicated relationships between the extent and duration of the primary nystagmic response and acceleration.

The extent of the nystagmic response has been shown by Jung and Tönnies (5) and Buys (1) to be directly related to intensity of acceleration and by Buys (1) to duration of acceleration. Duration of primary nystagmus was found by Rigotti and Sala (6) and Hauty and Wendt (4) to be directly related to duration of acceleration. Duration of primary nystagmus as a function of intensity of acceleration has been studied to a greater extent. With duration of acceleration brief and terminal velocities varying from very low to very high Buys (1), Jung and Tönnies (5), and Hauty and Wendt (4) have found little or no systematic differences in the durations of the primary nystagmus elicited by these different intensities of acceleration. Van Egmond (8), however, in presenting cupulometry as a more desirable method for clinical use, advances the hypothesis that since the magnitude of cupular deviation is determined by the intensity of acceleration and the duration of primary nystagmus is dependent on and proportional to the magnitude of deviation, the duration of primary nystagmus will accordingly be directly related to the intensity of acceleration. His results, in complete agreement with his hypothesis, are at variance with the findings of the above mentioned investigators.

Although considerable information has resulted from these earlier reports, there has been no systematic investigation where the duration of a given intensity of acceleration has been made to vary greatly and/or where a given terminal velocity has been attained by widely differing intensities of acceleration, and an adequate recording of eye movements accomplished. The present investigation attempts to supply these necessary quantitative data.

METHOD

Apparatus.—The *S* was seated on a rotating platform with head fixed at a forward tilt of

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about 15°. The vertical axis of the head was at the rotation axis. The platform which has been described by Wendt (9) was driven by an isolated power supply consisting of a 1-hp. electric motor and hydraulic transmission (Vickers-AA16801). The latter contains a variable displacement pump in which the displacement of the pump from the neutral point determines the speed of rotation and the rate at which this displacement is accomplished determines the acceleration.

A specific selected acceleration and velocity were produced as follows: An electrically driven gear train activated in a constant manner a gear rack which, in turn, mechanically displaced the pump. The rate at which the gear rack traveled determined the acceleration. This could be varied over a wide range by means of a system of reduction gears. Since the pump was displaced at a constant rate, a constant acceleration was expected. Measurements from records of platform speed exhibit an approximately linear function except for two very short periods, immediately after onset of acceleration and immediately before attainment of constant velocity. The distance the gear rack traversed determined the velocity of rotation. This was controlled by adjustable microswitch contacts which permitted an extreme range of velocities.

To decelerate the platform, the pump was returned from its displaced position to the neutral point by activating the gear rack in reverse. Thus, acceleration and deceleration were comparable if the same gear ratio was used or dissimilar if different gear ratios were used.

The recording of the vestibular nystagmus from both eyes through *closed lids* was accomplished by use of the Dodge mirror recorder (2). The main element consists of a small wood cube spring-fixed over the apex of the eyeball. When the eyeball moves in a horizontal plane, the cube is made to rotate in converse direction about its vertical axis. A mirror cemented on the distal surface of the cube reflects a light image which, in correspondence with the horizontal movements of the eyes, moves across the 4-in. aperture slit of the photokymograph-type camera. The optical distances involved were of such magnitude that 1° of ocular movement was represented by approximately 4.5-mm. excursion on the record. A constant-speed electric motor drove, at a rate of 9 mm./sec., 4-in. wide photographic paper upon which was also recorded the rotation of the platform, head movements, and time.

Experimental conditions and procedure.—This study utilized six widely varying degrees of acceleration to reach each of five widely varying velocities. The velocities used were 180°/sec., 90°/sec., 45°/sec., 22°/sec. and 12°/sec. Each of these velocities was attained by each of the following accelerations: 36°/sec.², 18°/sec.², 6°/sec.², 2°/sec.², and 1°/sec.² The lowest acceleration, 1°/sec.², is considerably above the threshold values reported by the various investigators. Tumarkin, for example, reports a threshold of 0.2°/sec.² (7). For each of the above velocities there was also used an additional acceleration. This was obtained by manually displacing the pump from neutral to a determined degree for any one of the above velocities and then activating the motor. The platform was thereby accelerated during the period of pickup in motor speed, and the final output velocity was achieved in approximately .5 sec. Thus, for 180°/sec., the acceleration was 360°/sec.²; for 90°/sec., 180°/sec.²; etc.

Owing to mechanical lag of the gear controls of the hydraulic transmission, the accelerations of very short duration were not strictly comparable in degree to those of longer durations. At 12°/sec., the gear ratio which was to effect an acceleration of 36°/sec.² had to attain this velocity in .33 sec. It required very slightly longer than this owing to the aforementioned lag in the system.

In the darkened room with recording apparatus attached and in tested working order, the photokymograph was activated for a period of 20–30 sec. This allowed a record of unstimulated eye movements for detection of any "drift." Rotation was then initiated, always to the right. After constant velocity was reached, rotation continued for 5 min. Deceleration was then initiated until cessation of rotation, following which, the photokymograph continued recording for 5 min. while *S* was stationary. Recording was continuous throughout these periods.

The acceleration and deceleration of a given trial were either identical with respect to intensity and duration of stimulation, e.g., acceleration and deceleration of 6°/sec.², or consisted of different stimulus conditions, e.g., acceleration of 6°/sec.² and deceleration of 1°/sec.² The justification for different levels of acceleration and deceleration per trial rests upon the experimental findings of Buys (1) and Hauty and Wendt (4) who separated the effects of acceleration and deceleration by a great enough period of constant velocity. Fifteen trials were given for training purposes. Following this, 45 trials, one per day, were conducted. Two or more records per experimental condition were thus obtained.

Throughout the trial, *E* maintained "chatter," if such was necessary, to aid *S* in maintaining an alert attentiveness which is essential to the continuous occurrence of maximal nystagmic response. When this alert attentiveness is absent, the result is a

wandering, nonconjugate movement of the eyes (11).

From the two or more records for the same experimental condition, the better one was selected on the basis of unbroken recording, i.e., the reflected images did not leave the aperture of the photokymograph, least irregularities were produced by mechanical disorder of recording, and least disruption by nonconjugate eye movements.

The measurements of this selected recorded response consisted of the total amount of slow-phase movement during each 2-sec. interval and the duration of this response. The former entailed the measurement in millimeters and summation per 2 sec. of each slow phase and the latter, the summation of these 2-sec. intervals making up the complete primary nystagmus.

Subjects.—To be suitable for this experiment, *S* must possess a facial and lid structure appropriate for this type of recording, freedom from lid tremor, and from wandering, nonconjugate movement of the eyes. Accordingly, from ten University of Rochester male undergraduates, three were selected after preliminary examination. Of these three, one, Subject A (*S*-A), was selected to provide results for all experimental conditions while the other two (B and C) were used for "spot-check" at critical levels of the stimulation dimensions.

Results

Reliability.—The inconsistency of the indicated amplitude of the slow phase as measured from the records may be due to true response variability, differences in magnification of the records depending on placement and adjustment of the recorders, and unrecognized interruptions by nonconjugate, wandering eye movements. The latter, even for the selected record, probably causes the greatest intraindividual variation in that its erratic occurrence operates to effect a momentary decrement in amplitude of slow phase.

Table 1 presents for *S*-A the degree of consistency in amount of slow phase for comparable stimulation periods of widely separated trials. Considering first the top row of response values (in millimeters), these were obtained by summating the slow-phase move-

TABLE 1

Correspondence of Response for a Given Duration of an Acceleration

Acceleration	Cumulative Duration in Seconds	Terminal Velocities (Degrees per Second)				
		12°	22°	45°	90°	180°
1°/sec.²	12	163	42	193	186	142
	22		101	570	439	374
	45			867	639	750
	90				1384	1959
2°/sec.²	6	67	26	59	66	61
	11		169	268	238	170
	22			662	478	415
	45				1442	1634
6°/sec.²	2	24	21	29	18	32
	4		73	122	74	85
	8			332	153	230
	15				473	668

TABLE 2

RESPONSE CHARACTERISTICS OF SUBJECT A

Terminal Velocity	Measure*	Accelerations					
		$t = 0.5''$	36°/sec.²	18°/sec.²	6°/sec.²	2°/sec.²	1°/sec.²
180°/sec.	DPN	70	62	80	88	124	202
	MRO	710	520	308	310	204	74
	POR	4	7	9	29	67	139
90°/sec.	DPN	60	104	68	86	122	150
	MRO	366	334	224	182	117	57
	POR	5	5	7	17	41	95
45°/sec.	DPN	86	56	64	82	90	108
	MRO	154	130	169	130	92	81
	POR	5	5	9	11	13	19
22°/sec.	DPN	64	56	52	56	86	74
	MRO	98	83	83	84	84	65
	POR	5	5	5	5	19	33
12°/sec.	DPN	48	46	**	62	48	70
	MRO	64	57	**	68	66	54
	POR	7	5	**	5	9	13

* DPN = duration of primary nystagmus (seconds); MRO = maximal response output (millimeters); POR = period of recruitment (seconds).
** Records discarded because of incompleteness of recording.

ment for the first 12 sec. for each of the five different terminal velocities where acceleration was 1°/sec.². The second row gives the summated response values for the first 22 sec. The third and fourth rows contain the summated response for the first 45 sec. and first 90 sec., respectively. The values for accelerations, 2°/sec.² and 6°/sec.², are to be interpreted in a similar manner, e.g., the top row for 2°/sec.² represents the summated response for the first 6 sec. of response; for 6°/sec.², the summated response for the first 2 sec. Only the three lowest accelerations are presented, since only these allow multiple comparisons.

The quantitative consistency of these records is far from perfect. They are adequate, however, for the conclusions to be drawn in view of the evidence of unidirectional trends as functions of stimulus characteristics and consistency with the pertinent findings of the previous studies of Buys (1), Jung and Tönnies (5), and Hauty and Wendt (4).

In Table 2 are presented measures of the nystagmic responses of *S*-A: (*a*) DPN (duration of primary nystagmus) represents the time from the onset of primary nystagmus to the point where the secondary nystagmus begins; (*b*) MRO (maximal response output) is given by the greatest amount of slow-phase movement occurring in a 2-sec. interval; and (*c*) POR (period of recruitment) is that period of time from the onset of primary nystagmus to the midpoint of the three consecutive 2-sec. intervals whose combined total response output is the greatest.

Duration of primary nystagmus.—One can inspect these values for a relation of nystagmus duration to intensity of acceleration by examining the data for the briefest accelerations given in Column 1. Here there appears to be no clear evidence of any consistent change in duration of nys-

tagmus with change in intensity of acceleration. The exception appears to exist at the lowest acceleration value where the primary nystagmus is of a shorter duration. The exception, however, is contrary to data of S-B and C. When one examines the durations given by the last two columns and the first three rows, it is immediately evident that duration of primary nystagmus is very much affected by the duration of acceleration. In the top row, for example, as acceleration is increased in duration from .5 to 180 sec., primary nystagmus is increased from 70 to 202 sec. At very low terminal velocities where all accelerations are fairly brief, nystagmus durations are roughly equal. It will be noticed, in fact, that for all terminal velocities achieved by accelerations ranging in duration from .5 to 30 sec., there appears little difference in nystagmus duration for this S.

Maximal response output.—Inspection of these data reveal the following relationships: (*a*) The first column and the top three rows reveal maximal speed of slow phase to have a direct relationship with intensity of acceleration. (*b*) The second, third, fourth, and fifth columns exhibit a direct relationship between maximal speed of slow phase and duration of a given intensity of acceleration. (*c*) The exceptions to these findings are found in the last column and the two bottom rows. Here both intensity and especially duration of acceleration are of low value. The mean response outputs were determined (total response output/total 2-sec. intervals). The relationships to be noted were identical with those given by the values of maximal response output. The periods of time necessary to reach the point of maximal output permit further response differentiation. Inspection of all rows reveals an inverse relationship between intensity of acceleration and the period of recruitment. In Columns 3, 4, 5, and 6 a direct relationship between duration of acceleration and the period of recruitment is seen. As noted in the first two columns where duration of accelerations is very brief, these points of maximal speed of slow phase are reached in about equal times.

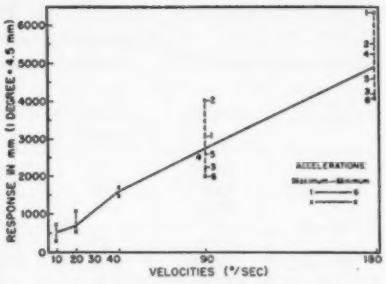

FIG. 1. Total response output as a function of total sensory input

Total output of primary nystagmus.—By total output is meant the amount of slow-phase movement obtained by measuring and summating every slow phase of the primary nystagmus. It is the total work done by the eyes. Figure 1 presents these data for S-A. The five terminal velocities are indicated at the abscissa and above each velocity are the total response outputs elicited by the six different accelerations which attained that given terminal velocity. The means of the values above each velocity were determined and are represented by the plotted curve. For 180°/sec. and 90°/sec., the highest velocities, there appears evidence of a direct relationship between intensity of acceleration and total output of primary nystagmus. For the three lower terminal velocities, no such relationship is present. For these velocities, the range of values is exceedingly short and no rank ordering is present. The linearity of the

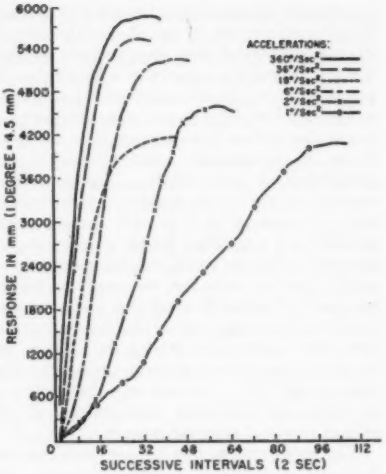

FIG. 2. Accumulative response curves for *S*-A (180°/sec. velocity)

plotted curve strikingly exhibits the direct relationship between total sensory input (terminal velocity) and total response output. It can be seen that so far as the total response output is concerned, the important determinant is not the intensity of acceleration but instead intensity of acceleration times its duration.

Primary nystagmic response curves.—To gain additional aspects of the obtained data, graphic representation was accomplished. Figure 2 presents for *S*-A the amount of slow-phase movement plotted accumulatively per 2-sec. interval for each of the accelerations where terminal velocity was 180°/sec.

It will be noted that as acceleration is decreased in intensity, the **S**-shaped curve form becomes more evident except that at 1°/sec.² the form is roughly linear. The data of the four lower terminal velocities were likewise plotted. The findings were: The responses elicited by a given intensity of acceleration were represented by a characteristic form of curve regardless of the duration of that acceleration except at the lowest terminal velocity.

Data obtained from Ss-B and C.—To provide data for comparison with that of *S*-A, two *Ss* were tested at critical points of the stimulus

TABLE 3

RESPONSE CHARACTERISTICS OF SUBJECTS B AND C

Terminal Velocity	Measure*	Accelerations					
		$t = .5''$		6°/sec.²		2°/sec.²	
		B	C	B	C	B	C
180°/sec.	DPN	36	38	52	50	106	100
	TRO	1857	1568	1739	1285	1185	1389
	MRO	250	289	150	96	73	64
	POR	5	3	17	23	42	58
90°/sec.	DPN	36	34	40	36	**	58
	TRO	733	1025	565	941	**	716
	MRO	180	173	93	130	**	44
	POR	1	3	14	13	**	23
45°/sec.	DPN	36	34	36	36	40	46
	TRO	271	449	359	360	309	375
	MRO	41	85	53	57	32	27
	POR	5	5	11	9	15	15

* DPN = duration of primary nystagmus (seconds); TRO = total response output (millimeters); MRO = maximal response output (millimeters); POR = period of recruitment (seconds).
** Records discarded because of incompleteness of recording.

dimensions. These data appear in Table 3, which includes the response characteristics presented for A, i.e., durations, total response output, maximal response intensity, and period of recruitment of primary nystagmus.

The major difference between A, B, and C is that of the greater extent and duration of the primary nystagmic response given by A. Because of this, A was selected to provide the data for all stimulating conditions which included very low intensities of acceleration and of short duration. Response curves, plotted for these two *S*s, were compared with those of A. The similarity in form and differentiation of form as a function of different intensities and durations of acceleration were strikingly evident. In view of these similarities and the fact that stimulus-response relationships given by the data of A were also exhibited by the responses of these two spot-check *S*s, it was felt that a reasonable basis for generalization had been obtained.

Periodicity of primary nystagmic response intensity.—At an acceleration of 1°/sec.^{2} and a terminal velocity of 180°/sec. *S*-A exhibited a phenomenon of periodic fluctuations of amount of slow-phase movement. Examination in Fig. 2 of the accumulative curve representing 1°/sec.^{2} reveals three roughly 60-sec. periods, within each of which amount of slow phase per unit of time increases up to a midpoint and then decreases. For this *S*, somewhat less clear-cut evidence of this periodicity was present under conditions of 2°/sec.^{2} to 180°/sec. and 1°/sec.^{2} to 90°/sec. This phenomenon was not apparent in the records of *S*s-B and C who were subjected to 2°/sec.^{2} as the lowest intensity of acceleration.

Discussion

General agreement has been indicated between the major stimulus-response relationships demonstrated in the earlier investigations discussed previously and those of the present investigation. In particular, considerable evidence supports the finding that no relationship appears to exist between primary nystagmus duration and intensity of acceleration.

Van Egmond (8), however, in presenting his technique of cupulometry which involves the stimulating conditions given by decelerating *S* within .5 to 2.0 sec. from greatly differing terminal velocities, does obtain a direct relationship between duration of primary nystagmus and intensity of acceleration. Resolution of this contradictory finding can probably be had when comparison of experimental techniques is made. Visual inhibitory effects are relatively greater the less the intensity of primary nystagmic response. If visual stimuli were operative in Van Egmond's experiments, his demonstrated relationship could be explained as being due to visual inhibition of the weaker or less intense nystagmic responses. There is, furthermore, another possibility in explanation of these results. The method of recording might be responsible. As was pointed out, the method used in this present study resulted in a magnified record of the *complete* primary nystagmus which, when the intensity of acceleration was very low, was made up for the most part of extremely small slow and fast phase excursions, less than one ocular degree but unmistakably vestibular nystagmus. These eye movements were most probably missed by Van Egmond who thus obtained only the portion of nystagmus in immediate juxtaposition to the peak of maximal response intensity.

The importance of this issue is occasioned by theoretical concepts of cupular mechanics. In this connection, deVries[3] presented the following views: When the duration of acceleration is short, i.e., less than 2 sec., the cupular property of flexibility and the friction produced by the canal bore and ampullar proximity are such that the degree of cupular deviation bears a linear relationship to the acceleratory force. Upon cessation of acceleration, the return of the cupula to its resting position takes the form of a negative exponential curve.

Van Egmond's finding of a marked direct relationship between intensity of acceleration and duration of primary nystagmus supports the possibility that the *rate* of cupular return is roughly constant. This follows from the reasoning that the greater the intensity of acceleration, the greater the initial cupular deviation. If the duration of primary nystagmus is likewise greater, then the cupula, in requiring more time to return to the resting position, returns at a somewhat constant rate.

The alternate possibility, which follows from the reasoning of deVries, is that the rate of cupular return is variable and directly related to the initial degree of cupular deviation. While the greater intensity of acceleration results in a greater initial cupular deviation, the return of the cupula is also greater in speed. The findings of Buys (1), Jung and Tönnies (5), Hauty and Wendt (4), and of the present study provide the

[3] Hl. deVries of the University of Groningen discussed certain views concerning the physical properties of the receptor during a visit to the University of Rochester. Since these views are as yet unpublished, any misrepresentation is the fault of the writer.

evidence for this possibility. Regardless of the intensity of acceleration (where duration of acceleration is brief), the durations of primary nystagmus are roughly constant; hence, the rate of cupular return would have to be directly related to degree of cupular deviation and, therefore, to intensity of acceleration. It will be noted that both of these hypotheses concerning duration of primary nystagmus preclude the possible influences of central mechanisms.

The present investigation also demonstrates additional relationships concerning the function of stimulus duration and the integrated function of stimulus intensity and duration. Regarding the former, the data on maximal and mean response outputs and periods of recruitment have indicated an effect which was first noted by Buys (1). As a constant acceleration continues in time, the intensity of primary nystagmus likewise increases up to a particular point. It can be described as an *accumulative excitatory effect.* It is difficult to explain this phenomenon as arising from events occurring at the peripheral level. It is believed that the cupula, having been deviated by a given intensity of constant acceleration, will maintain this initial exact deviation throughout the duration of this constant acceleration. With the cupula "fixed" at a particular deviation, the accumulative excitatory effect which follows as the constant acceleration continues can be more easily attributed to the central mechanisms.

Equally interesting is the total sensory-input–total response-output relationship. It has been seen, especially at the lower sensory-input levels, that the total amount of slow-phase eye movement bears a remarkably direct relationship with the total sensory input. So long as the product of work done or power expended on the receptor is a constant, so will the work outputs be approximately equal regardless of the intensity and duration of acceleration.

The observed periodicity of primary nystagmic intensity was a particularly unexpected finding. In fact, its apparent uniqueness in vestibular research necessarily precludes further comment by the writer at this time. Wendt (10), in discussing these results, has briefly presented a possibly significant interpretation.

Summary and Conclusions

Of three male undergraduates who were selected after appropriate preliminary examination, one was subjected to five different velocities of rotation, 180°/sec. to 12°/sec., reached by each of six different accelerations, a total range of 360°/sec.^{2} to 1°/sec.^{2} The other two *Ss* served in spot-checks at critical stimulating conditions. The head was fixed so that forward inclination was approximately 15°. The trial consisted of a selected value of acceleration followed by 5 min. of constant rotation at a selected terminal velocity, then, a selected value of deceleration, and following this, a 5-min. stationary period. The entire sequence of nystagmic responses (primary and secondary of positive acceleration and primary and secondary of negative acceleration) were continuously recorded by the mirror recorder for recording eye movements through the closed lids. Two or more trials per stimulating condition were given on widely separated days. From these records, that record evidencing the greatest completeness and freedom from artifact was selected and the total amount of slow-phase eye movement was measured for each 2 sec. of the primary nystagmus up to the point where the secondary nystagmus began.

Conclusions derived:

1. Intensity of acceleration was directly related to the extent of eye movements occurring in primary nystagmus but did not modify the duration of this response.

2. Duration of acceleration was directly related to the duration and to the extent of eye movements of primary nystagmus, and to the period of recruitment of eye movements. These latter two relationships were attributed to an accumulative excitatory effect, a function of central mechanisms.

3. Total primary nystagmic response output was directly related to total sensory input, i.e., the product of acceleration and its duration. When total sensory input is reduced by a half, total primary nystagmic response output is reduced by a like

fraction regardless of the intensity and duration of acceleration used to achieve the given reduced total sensory input.

4. Interindividual variation was of considerable extent with greatest variation occurring in the duration and amplitude of slow-phase movement of the primary nystagmus. Far less variation existed in the forms of the plotted response curves or differentiation of these forms as a function of acceleration intensity.

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GENERALIZATION AND EXPOSURE TIME AS RELATED TO AUTOKINETIC MOVEMENT [1]

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The autokinetic phenomenon, in accordance with which a stationary light source viewed against total darkness appears to move about in an unpredictable way, has been widely employed in experimental social psychology in recent years, following Sherif's demonstration (**5**) of its utility in solving questions of norm formation and modification. The general procedure in all such studies is basically the same: An *S* is permitted to form a judgmental norm under one condition and in a subsequent session the modification of this norm due to various experimentally introduced factors is studied. Many, though not all, of these studies have been designed to observe the behavior of *S*s with different individually established norms when they are placed together in a group situation. In Sherif's original work, *S*s were allowed to establish their norms in an individual autokinetic session, no attempt being made to influence the magnitude of the particular norm, after which individuals with different norms were selected for group sessions.

The desire to investigate the influence of other factors determining the response has, however, led to persistent attempts to predetermine in some way the magnitude of the norm for any particular *S*. Perhaps the most widely adopted method has been the use of a confederate in the initial session who, by the nature of the judgments he gives, causes *S* to modify his norm in the desired direction. The difficulty with using this technique to establish a predetermined standard lies in the fact that individual *S*s have different levels of anxiety, different degrees of suggestibility, and react differentially to the confederate. Sherif concludes from his attempts in this direction that *S*s may be influenced to perceive an indefinite stimulus field in terms of an experimentally introduced norm but, "The degree of the influence may be different in different subjects" (**6**, p. 97). Bovard, using similar conditions, came to the identical conclusion: that the general effect of the introduction of a social norm was to shift the mean of judgments in the suggested direction but, ". . . the amount of shift varied greatly from one subject to another" (**2**, p. 69).

Recent leadership studies conducted in the Urban Life Research Institute of Tulane University have used as one criterion of leadership the performance of *S*s judging autokinetic movement as group members, after they have established individual norms of judgment. In the pursuit of these studies three questions emerged, namely: (*a*) Is it possible to establish a predeter-

[1] The study is one of a series carried out under ONR Contract Nonr-475(01) with Tulane University that provides for a systematic investigation of the relationships holding between personality, learning, and social variables. The project, under the direction of J. H. Rohrer, is a part of the research program of the Neuropsychiatry Branch, Bureau of Medicine and Surgery, U. S. Department of Navy. Captain George N. Raines, (MC) USN, is the technical officer for the project. While this paper constitutes a technical report to ONR, the interpretations presented herein are those of the authors and do not necessarily represent those of the sponsoring agency, the Department of the Navy.

mined norm through a training procedure, utilizing real movement of a point of light within a stationary visual framework; (*b*) will this judgmental norm influence the judgments of the apparent movement of a stationary point of light in an otherwise dark room, i.e., will stimulus generalization occur to the autokinetic phenomenon; and (*c*) what is the influence of the exposure time of the stationary stimulus light on the extent of autokinetic movement.

The present paper reports an investigation of these questions, and discusses some implications of the results of this study for research utilizing the autokinetic phenomenon.

Method

Subjects.—The 42 *S*s for this experiment were Navy enlisted men under arrest and awaiting court martial at the time of the experiment. They were assigned to participate on the basis of availability. Although they were not volunteers, all *S*s were cooperative. They were unaware of the purpose of the study.

Experimental room apparatus.—The experimental room was a completely lightproofed, air-conditioned, sound-dampened room, 30.5 ft. long and 10.5 ft. wide. Except for the stimulus light it was completely darkened during the experiments.

The stimulus for training trials utilizing real movement was a pinpoint of light produced by a 6-v. radio dial bulb, showing through a hole 2 mm. in diameter, which was covered with diffusing tissue. The distance, speed, and direction of light movement could be varied. Duration of the light-exposure time was a function of distance moved and speed of movement, because the apparatus was built to expose the light when it started to move and to turn it off when a set distance had been traversed. The *S* was seated 18 ft. from the light.

Movement of the light was accomplished by a reversible, variable speed motor which turned a screw and moved the light along a slide shaft. The distance of movement was determined by an adjustable stop on the slide shaft which tripped a microswitch to turn off the light and reverse the motor causing the light housing to return to the starting position.

Maximum movement possible was 8 in.; rate of movement was variable from .2 in./sec. to 1.9 in./sec. The motor, light housing, and slide shaft were mounted on a stand with a single bolt which permitted the functional parts of the apparatus to be turned through 360°. This enabled *E* to set the apparatus to move the light in any direction, the course traveled being in each case on a diameter of the framework provided.

Two luminous frames were used in the first (i.e., "training") session of the experiment. They were constructed from ¼-in. Lucite rods moulded into circles and painted with luminous paint. The larger had a diameter of 14 in., the smaller a diameter of 6 in. They were placed 8 in. in front of the light with the center of the frame coinciding with the axis around which the apparatus revolved.

A stationary light source of approximately the same intensity as the moving stimulus was substituted in the apparatus during the second session of the experiment. This permitted exposure of the stationary light for the desired time intervals accompanied by the same sounds as had been present when an actually moving stimulus was employed.

Experimental design.—The design utilized two judgment sessions for each *S:* an initial training session wherein he was required to make 50 judgments[2] of the extent of movement of a light which actually moved a constant distance (2 or 8 in.) within a luminous circular framework; and a second, "autokinetic," session in which a like number of judgments were required, but in which the stimulus was a stationary pinpoint of light that was exposed for a constant interval (3, 5, or 7 sec.) in the darkened room *without* the luminous frames. There were thus six possible combinations of the training and test variables. Seven *S*s were assigned at random to each combination.

Training sessions.—There were two training distances. In TD_2 21 *S*s were required to make 50 judgments of the extent of movement of a light which moved 2 in. within a stationary luminous circular framework which was 6 in. in diameter. The direction of movement for each trial was randomly varied by *E*. The light was exposed for 7 sec. with a 7-sec. interval between exposures.

In TD_8 21 *S*s experienced the same general conditions as did *S*s in group TD_2, except that they were presented with a stimulus that moved 8 in. within a stationary luminous framework that was 14 in. in diameter.

The varied direction of the movement of the light in the training session represented an attempt to familiarize *S*s with the irregular nature

[2] Results of a previous study determined that, compared with 30 and 70, 50 was the optimum number of judgments for a minimum coefficient of variation.

of the subsequent autokinetic phenomenon and to confound any systematic fixation of their response tendencies for a given direction. The two different-sized frames were used so that the smallest distance between the frame and the light source would be the same for the two groups. The light for each group started moving from a point 2 in. from the center of the framework and moved on a diameter *part* of the way across the circumscribed field. For Group TD_2 the *starting* point was 1 in. from the circumference of the framework; for Group TD_8 the *ending* point was so located.

Test sessions.—There were three exposure times in the test sessions. Group ET_3 consisted of 14 *Ss*, half of them from Group TD_2 and half from Group TD_8, who were required to make 50 judgments of the extent of movement of a light that was exposed for 3 sec. with a 3-sec. interval between exposures. Group ET_5 consisted of 14 *Ss*, divided in the same manner as Group ET_3, who made 50 judgments of the extent of movement of a light that was exposed for 5 sec. with a 5-sec. interval. Group ET_7 consisted of 14 *Ss* divided in the same manner as Group ET_3 *Ss* and who experienced the same general conditions except that the stimulus was exposed for 7 sec. with a 7-sec. interval.

Training session.—The following instructions were read to each *S* just before he entered the experimental room:

> This work is being done for the Office of Naval Research. We are interested in finding out how accurately you can judge the movement of a light in the dark. I am going to show you a pinpoint of light which will be automatically moved by a machine. As soon as the light goes out, I want you to tell me how far it moved, in inches. It is important that your judgments be accurate, so please do the best you can at all times. The light will move inside a luminous framework which you will see directly in front of you. The framework is (6, 14) inches across. Now remember, when the light goes on, watch it carefully. As soon as it goes off, tell me the number of inches it moved, and then wait for it to go on again. Are there any questions?

Any questions were answered and *S* was led into the darkened room and seated near the entrance in an upright chair facing the apparatus. The instructions were informally repeated while dark adaptation was taking place. When the training session was completed, *S* was led out of the room to a waiting room where he could read magazines, smoke, and relax.

Autokinetic session.—Each *S* was brought back into the experimental room approximately 30 min. after completion of his training session. The instructions for this session were presented informally to *S* after he was seated in the dark room. He was requested to give judgments of the extent of movement of a point of light in the absence of the luminous framework.

Scoring.—The scores were in terms of inches of movement as reported by *S*. The training session score (M) is the median of the 50 judgments recorded for *S* during the training session, and the autokinetic session score (A) is the median of the 50 judgments recorded for *S* during the autokinetic session.

TABLE 1

MEAN MOVEMENT SCORES IN TRAINING SESSION*

Exposure Time in Test Session	Training Distance in Training Session			
	2 In.		8 In.	
	Mean	*SD*	Mean	*SD*
3 sec.	2.89	1.98	8.21	1.68
5 sec.	3.14	.69	8.14	.69
7 sec.	2.93	1.02	9.29	.95
Total	2.99	1.28	8.55	1.24

* $N = 7$ for each cell entry.

RESULTS

Table 1 presents the mean movement scores for each group in the training session. Differences exist between the training distance and the mean of training-session (M) scores

TABLE 2

MEAN AUTOKINETIC SCORE IN TEST SESSION*

Exposure Time in Test Session	Training Distance in Training Session			
	2 In.		8 In.	
	Mean	*SD*	Mean	*SD*
3 sec.	2.64	1.75	6.64	2.17
5 sec.	4.36	1.31	7.00	2.00
7 sec.	4.68	1.82	9.07	4.89
Total	3.89	1.81	7.57	3.31

* $N = 7$ for each cell entry.

TABLE 3

ANALYSIS OF VARIANCE OF *M* AND *A* SCORES*

Score	Source of Variation	*df*	Mean Square	*F*
Training session (*M*)	Between TD groups	1	324.54	204.11**
	Within groups	40	1.59	
	Total	41		
Autokinetic session (*A*)	Between TD groups	1	142.09	21.30**
	Between ET groups	2	17.47	2.62
	Interaction, TD × ET	2	2.95	
	Within groups	36	6.67	
	Total	41		

* The hypothesis of homogeneous variance is not rejected at the .01 level of confidence by the Bartlett test for either the *M* or the *A* scores.
** Significant beyond the .01 level of confidence.

for the *S*s. The *S*s trained with a light that moved 2 in. had a mean judgment of 2.99 in., and the *S*s trained with 8-in. movement had a mean judgment of 8.55 in., indicating a tendency to overestimate the distance. The difference between the obtained mean score and the true score (or training distance) falls beyond the .01 level ($t_{2,1} = 2.91$) for the TD_2 group, and at the .05 level ($t_{2,1} = 1.72$) for the TD_8 group. This is evidence for rejecting the hypothesis that the mean score for a group of *S*s does not differ from the actual distance the light moves. However, the score for 40 of the 42 *S*s was within 2 in. of the training distance. This would indicate that the procedure is adequate for establishing a predetermined norm within these limits.

Table 2 presents the mean autokinetic scores for each group in the test session. A trend may be observed for the scores to increase with the increase in exposure time. However, the outstanding feature of the table is the general consistency of the judgments of the *S*s for the two sessions. In order to evaluate these various differences, analyses of variance and covariance were made using the data of Table 1. The results of these analyses are presented in Tables 3 and 4.

The differences between the paired *M* and *A* measures for each of the *TD* groups fall short of significance ($p > .05$ for TD_2; $p > .05$ for TD_8) when

TABLE 4

ANALYSIS OF COVARIANCE AND TESTS OF ADJUSTED MEANS*

Source of Variation	*df*	Sums of Squares and Products			Errors of Estimate		
		M^2	*MA*	A^2	*df*	Mean Square	*F*
Between TD groups	1	324.54	214.74	142.09	1	.39	—
Between ET groups	2	2.48	8.79	34.94	2	12.39	1.93
TD × ET	2	3.51	3.75	5.90			
Error	36	57.77	33.11	244.12	35	6.43	
Total	41	388.30	260.39	427.05			

* The differences among the group regressions are not significant when tested against the mean-square deviation from individual group regressions. This indicates that the regression coefficients may be considered members of a common population and justifies the use of the average regression within groups in the analysis of covariance.

evaluated with the sign test (3), providing evidence of the occurrence of stimulus generalization from the first to the second situation. The difference between the means of the movement (*M*) scores for the two groups with different *TD*'s is highly significant. The autokinetic (*A*) scores also differ significantly for these two groups. Furthermore, the analysis of the errors of estimate for the regression of the *M* scores on the *A* scores in Table 3 is not significant, indicating that the differences in *A* scores can be accounted for by the differences in *M* scores. It is apparent from these findings that the norm established in the training session was effectively generalized to the judgments made in the autokinetic session.

Figure 1 shows the influence of exposure time on the *A* scores. Increasing the exposure time for the autokinetic stimulus appears to produce a trend toward larger *A* scores. As Table 3 indicates, however, the differences for the three Exposure Time (ET) groups

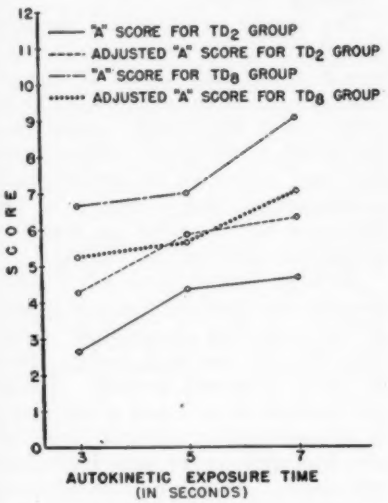

FIG. 1. The autokinetic-movement score (*A*) as a function of exposure time

on the *A* scores are not significant at the .05 level of confidence. The trend for the two TD groups is similar; the mean square for the interaction of TD and ET for the *A* scores is not significant at the .05 level as shown in Table 3.

The adjusted *A* scores included in Fig. 1 represent the scores that would be predicted if each of the six ET groups had a common *M* score of 5.77, the mean for all 42 *S*s. The analysis shown for the errors of estimate in Table 4 indicates that the adjusted *A* scores do not differ significantly for different ET's. It has already been pointed out that the adjusted *A* scores do not differ significantly for the TD's.

The consistency of the trends for the ET's is inconclusive evidence for the operation of exposure time as a factor in determining judgments in the autokinetic session; however, future work along these lines using a wider range of exposure times would likely result in statistically reliable differences.

DISCUSSION

There is considerable similarity between autokinetic movement and actual movement of a similar light source. It occurred to the present investigators, therefore, that such actual movement might be used to train *S*s to a desired norm. In preliminary explorations *S*s were asked to judge such actual movement under conditions otherwise identical with an autokinetic session. It was found, however, that the perception of the real movement experimentally introduced was confounded with perception of autokinetic movement in such a way as to preclude the prior determination of any particular *S*'s norm, a difficulty previously reported by Proshansky and Murphy (4). In order to overcome these autokinetic effects

in the training session it was necessary to increase the number of discriminal cues (i.e., "structure") in the situation by adding a visual framework and by specifying the size of this framework to the *S*. Under these conditions it was possible to build up in *S*s a response norm which, although significantly different (statistically) from the predetermined norm, was sufficiently close to it for practical purposes. That is to say, our whole interest in such training has been to obtain *S*s with predictably different norms so that they might be matched on other factors for group autokinetic sessions. By use of the present procedures it has been found that *S*s can be trained to an 8-in. norm which approximates within a range of ± 2 in. that which is desired, and to a 2-in. norm which approximates within a range of + 2 in.

Having established that it is possible to build up norms in the manner described, there was still no certainty that the norms would be generalized to later autokinetic sessions. For, while the situations are very similar (the similarities being maximized by the conditions of the present experiment), there are still considerable differences, the most obvious being the nature of movement perceived in the two situations. Autokinetic movement was seen by all *S*s, but they did not all see it as the same type of movement. Typically reports are made (5) of differences in direction, constancy, distance, uniformity, and linearity (i.e., for some the movement is curvilinear while for others it is straight).

The question arose as to whether the *S*s should be told in their autokinetic session that they were judging movements of the same light they had previously seen in the training session. To do so would have constituted an additional emphasis upon the similarities of the two situations had the information been accepted, but it was feared that the more astute *S*s might be concerned with the differences and not accept the information. Neither was it desirable to tell them that the light they saw in the autokinetic session was *not* the same, for this would have merely emphasized the differences. In consequence, the instructions were left neutral; *S*s were told (at the beginning of the autokinetic session) that they would be asked to judge the distance of *a* light movement, and the similarities of the situation and procedure were pointed out to them.

Under these conditions it was found that stimulus generalization occurred to a very marked extent. Not only was it found that no significant differences existed between the training and the autokinetic norms, but it was found in the covariance analysis that the differences between the autokinetic norms of the *S*s can be accounted for by the variation in their initial "training" norms.

The second experimental variable investigated in the present study is the length of exposure of the stationary stimulus light in autokinetic-judgment trials. It is remarkable, considering the extent to which this phenomenon has been employed in psychological investigations, that a search of the literature has revealed no previous systematic study of this variable.

All investigators have noted that, for most *S*s, the light does not appear to start moving immediately upon being fixated, but that, rather, there is a delay of several seconds. Adams (1) determined the mean of this delay in a large number of trials to be 6.1 sec., but with rather large individual differences. In an effort to rule out individual differences in this initial delay, most *E*s have employed a con-

stant interval *after* S signals the beginning of movement. Others have used a rather constant interval of long duration as a method of minimizing the effects of differences in onset of perceived movement. In the present situation it was felt that the prior experience of the *S*s with a light which *did* move immediately upon being presented, in addition to the facilitative auditory stimulus provided, probably acted to curtail the extent of this delay. This was borne out by an absence of zero movement responses for the *S*s.

That the duration of exposure will influence the extent of observed movement (at least within certain limits which have not been determined) would follow from Adams' observation that "Ordinarily the light kept moving as long as it was fixated . . ." (1, p. 11). Previous studies by the present *E*s had suggested that for the autokinetic exposure time used (7 sec.) individuals with a previously established low movement norm were more likely to raise their norm than were individuals with a previously established high norm. It was felt that by changing the exposure time, these tendencies might be equated for the two groups. It should be emphasized that in the present work there was no attempt to establish the limits within which exposure time influenced extent of movement, nor to describe the function in any detail. The questions, rather, were whether this factor was operative, and, if so, whether the magnitude of judgments obtained in the autokinetic situation could be varied by manipulation of it. To answer the questions exposure times of 3, 5, and 7 sec. were used with an identical sound accompaniment in each case. Despite the small differences in exposure time which were employed, the consistency of the trend obtained (as revealed in Fig. 1) leads to the expectation that by increasing the range of exposure times or by using a larger number of *S*s significance would be found.

Summary

A method has been demonstrated for establishing stable predetermined norms of judged extent of light movement which will generalize to judged extent of autokinetic movement. The findings also suggest that duration of exposure of an autokinetic stimulus is a factor which contributes to the magnitude of judgments obtained.

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THE STRENGTH OF SENSORY PRECONDITIONING

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As Birch and Bitterman (1) noted in a recent analysis of the nature of reinforcement, the phenomenon of sensory preconditioning poses a rather difficult problem for Hullian theory. Consider, for example, an experiment by Brogden (4). Two stimuli, a tone and a light, are repeatedly paired in the first stage of training, and in the second stage one of these stimuli, say the light, is paired with shock to the forelimb until it comes to elicit a flexion response. Finally, the tone is presented alone and the flexion response appears despite the fact that tone and flexion have never before occurred in temporal contiguity. As Brogden remarked: "The experience of two contiguous sensory stimuli completely divorced from any phasic activity is frequent to any organism. If one of these stimuli becomes the signal for the response of a given reaction-pattern, the other will then elicit a similar response" (4, p. 331).

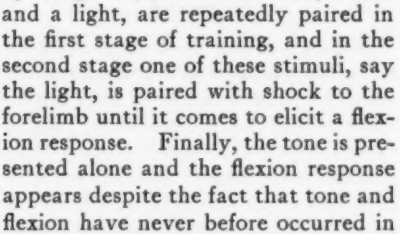

FIG. 1. An account of sensory preconditioning in terms of Hullian theory: R_L, any implicit response to light; S_{RL}, proprioceptive stimuli arising from R_L. Light is assumed to produce a need which its termination reduces, and this need reduction is responsible for the connection Tone $\rightarrow R_L$ in Stage I. In Stage II, both light and S_{RL} are connected to flexion as a consequence of the need reduction produced by shock termination.

In order to account for this phenomenon in terms of Hullian theory, several *ad hoc* assumptions must be introduced. Specifically, in the case of Brogden's experiment, it must be maintained that the light elicits some characteristic (probably implicit) response (R_L) which becomes conditioned to the tone in the first stage of training (Fig. 1). To explain the Tone $\rightarrow R_L$ connection, it must be assumed that the termination of the light provides the necessary need reduction. If it is further assumed that R_L is elicited by light in the second stage of the experiment, and that the proprioceptive consequences of R_L (S_{RL}) become connected to flexion (the need reduction being provided by shock termination[1]), the events of the final stage of the experiment (Tone $\rightarrow$ Flexion) are understandable: Tone $\rightarrow R_L \rightarrow S_{RL} \rightarrow$ Flexion.

Since the need aroused by light, and consequently the magnitude of need reduction ensuing upon light termination, cannot be great, the Tone $\rightarrow R_L$ connection cannot be assumed to be very strong, because ${}_sH_R$—in the earlier system (8) or ${}_sE_R$ in the later system (9)—is said to be positively related to the amount of need reduction. On the principle that a chain is no stronger than its weakest link, it follows that sensory preconditioning should be a weak and unstable affair. There has been an unfortunate tendency to accept this proposition (10,

[1] Several recent researches provide evidence in support of the conclusion that the onset rather than the termination of a noxious UCS is the crucial factor in classical conditioning (3, 11).

12) on the basis of quite inadequate evidence; the study of sensory preconditioning has not progressed beyond the earliest stage, and the negligible effects sometimes reported (**5, 13**) may reflect only the fact that optimal conditions have not been employed. Instructions to the subjects, explicit or implied, undoubtedly play an important role, particularly in experiments which utilize voluntary responses (**6**). It might also be suspected that the temporal relation in which the stimuli are presented is an important variable, as it is in classical conditioning. Nevertheless, it has been the common practice to employ *simultaneous* presentation of the neutral stimuli in the first stage of sensory preconditioning experiments—a temporal relationship which produces little, if any, conditioning of the classical kind. That these experiments have, on occasion, given positive results may be taken as evidence for the strength rather than the weakness of sensory preconditioning. Data such as those of Ellson (**7**) suggest that sensory conditioning may have fairly stable consequences. The experiment here reported was designed to provide a direct comparison of the strength of sensory preconditioning with that of classical conditioning.

Method

The conditioning and extinction of the galvanic skin response to shock were studied in 40 undergraduate men and women at the University of Texas who were divided randomly into two equal groups. The apparatus employed, which provided continuous graphic records of skin resistance, was a Brush DC amplifier (Model BL 932) and two-channel ink-writing oscillograph (Model BL 202) coupled with a specially constructed external scaling and balancing circuit. A detailed description of this circuit is presented elsewhere (**2**). The entire apparatus was linear over the range of resistances measured, and it was so calibrated that a change in resistance of 50 ohms produced a deflection of 1 mm. on the chart paper. Deflections could be read to the nearest .5 mm. The stimuli employed were presented automatically by means of stepping switches and recorded on the second channel of the oscillograph. Two 110-v., 15-w. lamps (L_1 and L_2) mounted one beside the other on a panel were employed as neutral stimuli, and a 1-sec., 3.5-ma. shock (from a 700-v. transformer through a high series resistance) served as the UCS.

For each of the 20 *S*s of Group I there were 20 unreinforced presentations of stimuli in the first stage of the experiment. For half of these *S*s (Group IA) L_2 was presented alone on 10 of the trials and the sequence L_1–L_2 on the other 10 trials. The two kinds of presentation were randomized over the total of 20 trials. The duration of each stimulus was 2 sec. Thus, in the case of L_1–L_2, L_1 was on for 2 sec. and then L_2 was on for 2 sec., the onset of L_2 coinciding with the termination of L_1. In the second stage of training L_2 was paired with shock over a series of 10 trials. Again L_2 was 2 sec. in duration, and its termination coincided with the onset of the UCS. In the third stage of the experiment (extinction) there were 10 presentations of L_1 alone and 10 presentations of L_2 alone. Each stimulus was 2 sec. in duration, and the two stimuli appeared in random sequence over the series of 20 trials. For Group IA, therefore, L_1 served as the sensory preconditioned stimulus (PCS) and L_2 served as the classically conditioned stimulus (CS). The third stage of the experiment served to compare the strengths of the two stimuli, with each *S* serving as his own control. For Group IB, the procedure was identical, except that L_1 served as the CS and L_2 as the PCS. That is, in the first stage the presentations were L_1 alone or the sequence L_2–L_1, and in the second stage L_1 was paired with shock. These procedures are summarized in Table 1. For half the *S*s of Group I considered as a whole the sequence of stimuli in the extinction stage was PCS, CS, PCS, CS, CS, CS, PCS, PCS, CS, PCS, CS, PCS, CS, PCS, PCS, PCS, CS, CS, PCS, CS. For the other half of the *S*s the reverse sequence was used: CS, PCS, CS, PCS, PCS, etc. In all stages of the experiment a fixed intertrial interval of 30 sec. was employed.

One important feature of this design should be noted. If in the first stage of the experiment the to-be-conditioned stimulus had not been presented, the relative strength of the PCS might have been significantly reduced. In such a design (e.g., L_1–L_2 unreinforced and then L_2 reinforced) L_1 might conceivably have functioned as a conditioned inhibitor for the galvanic response.

The 20 *S*s of Group II served as a control against the possibility that failure to find a sig-

TABLE 1

EXPERIMENTAL DESIGN*

Stage	No. of Trials	Group			
		IA	IB	IIA	IIB
I	10	L_1–L_2	L_2–L_1	L_1	L_1
	10	L_2	L_1	L_2	L_2
II	10	L_2–Shock	L_1–Shock	L_2–Shock	L_1–Shock
III	10	L_1	L_1	L_1	L_1
	10	L_2	L_2	L_2	L_2

* In Stages I and III the two types of stimulus presentation (e.g., L_1–L_2 and L_2 in Stage I for Group IA) were given in random order over the series of 20 trials.

nificant difference between PCS and CS in Group I might be due to stimulus generalization or unreliability of measurement. The procedure for Group II differed from that for Group I only in that there was no pairing of stimuli in the first stage. L_1 and L_2 were presented individually in random order over a series of 20 trials, and then one of the two stimuli was paired with shock in the second stage. For Group IIA, L_2 served as the CS and L_1 as the generalization stimulus (GS), while the functions of the two stimuli were reversed for Group IIB (Table 1). The extinction series thus made it possible to compare the strengths of GS and CS, with each *S* serving as his own control. For half the *S*s of Group II considered as a whole, the order in which the two stimuli were presented during extinction was: GS, CS, GS, CS, CS, CS, GS, GS, CS, GS, CS, GS, CS, GS, GS, GS, CS, CS, GS, CS. The reverse sequence was used for the other half of the *S*s: CS, GS, CS, GS, GS, etc.

The *S*s were brought individually into an electrically shielded, soundproof, semidarkened room and seated in a deep, leather-upholstered chair. GSR electrodes (saline-saturated sponge-rubber disks set in plastic cups) were attached to the dorsal and palmar surfaces of the left hand after the skin surfaces had been rubbed with electrode paste. Shock electrodes were fastened to the right wrist. The *S*s were told that some simple physiological measurements were being made and were instructed to sit quietly in the chair and to attend to the lamps in the panel before them. They were informed that shock would be administered occasionally, that its intensity was not great enough to be disturbing to most people, but that they should feel free at any time to ask that work be discontinued if they found the shock too unpleasant. (No *S* made this request.) After *S* had settled in the chair and the apparatus had been adjusted, the experimental series was begun.

RESULTS AND DISCUSSION

In Fig. 2 the course of extinction in each group is plotted separately for each stimulus in terms of median response magnitude as a function of paired trials (since order effects were balanced out in pairs of trials). The curves for Group I show no consistent difference between responses to classically conditioned and sensory preconditioned stimuli. The curves for Group II show a consistently higher level of response to the classically conditioned stimulus than to the generalization stimulus.

For purposes of statistical evaluation two scores were computed for each of the *S*s of Group I: total response to the ten presentations of the classically

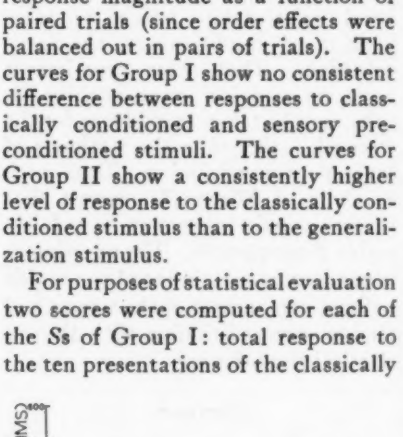

FIG. 2. The course of extinction in the two groups: *CS*, conditioned stimulus; *PCS*, sensory preconditioned stimulus; *GS*, generalization stimulus.

conditioned stimulus and total response to the ten presentations of the preconditioned stimulus. Analogous scores were computed for each *S* of Group II: total response to the ten presentations of the conditioned stimulus and total response to the ten presentations of the generalization stimulus. For Group I the mean response to CS was 1325 ohms and the mean response to PCS was 1275 ohms. The difference between the two distributions of scores, evaluated by Wilcoxon's nonparametric method for paired replicates (**14**), failed to approach significance (sum of negative ranks = 84, $p > .05$). For Group II the mean response to CS was 1490 ohms and the mean response to GS was 687 ohms. The difference between these distributions, evaluated by Wilcoxon's method, was highly significant (sum of negative ranks = 4.5, $p < .01$). Since the mean response to CS in Groups I and II was of the same order of magnitude, the reactivity of the two groups was considered similar enough to warrant cross-comparisons. By Wilcoxon's method for unpaired replicates (**14**) response to CS in Group I was significantly greater than response to GS in Group II (sum of ranks = 331, $p < .05$). By the same method response to PCS in Group I was significantly greater than response to GS in Group II (sum of ranks = 334, $p < .05$).

It may be concluded from these results that a sensory preconditioned response tendency is not inevitably weaker than a response tendency established by the classical procedure. That the relative strength of sensory preconditioning in the present experiment cannot be attributed to stimulus generalization or to unreliability of measurement is demonstrated by the highly significant differentiation found in the control group. The results here presented are understandable in terms of a sensory-sensory contiguity theory but find no ready explanation in Hullian terms.

Summary

The extinction of the galvanic skin response was studied in an experiment designed to measure the strength of sensory preconditioning. Two groups of 20 *Ss* each were employed. In Group I no significant difference was found between responses during extinction to two stimuli, one of which was classically conditioned and the other sensory preconditioned. In Group II response to a classically conditioned stimulus was significantly greater than response to a second stimulus which functioned as a control for stimulus generalization. The data provide no support for the concept of sensory preconditioning as a weak and unstable effect.

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AMOUNT OF PRIMARY REWARD AND STRENGTH OF SECONDARY REWARD [1]

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Early studies demonstrated the existence of a secondary-reward effect; recently the emphasis has shifted to an analysis of the variables affecting the strength of secondary rewards. The purpose of the present pair of studies was to determine the relationship between secondary-reward strength and the amount of primary reward with which reward stimuli have been associated. The only information on this problem is Wolfe's finding (2) that chimpanzees would learn to choose a token worth two grapes in preference to tokens worth one or no grapes.

Experiment I studied the differences in the effects of stimuli associated with high and low rewards on resistance to extinction. In Exp. II the effects of such stimuli on the acquisition of a new response were examined.

Experiment I

Subjects and Apparatus

The *S*s were 64 naive male albino rats from 90 to 143 days old weighing 148 to 333 gm. before training.

The apparatus was a straight alley runway 4 in. wide, 56 in. long, with interchangeable end boxes differentiated as to brightness and mode of entry. The starting box was 4 × 7 in. and the end boxes were 8 × 8 in. The inside walls were 4½ in. for all equipment except the white end box, which had 6-in. walls. One guillotine door separated the starting box and runway; another was placed 8 in. from the end of runway. A curtain hung 1 in. from the runway end. All the apparatus except the end boxes was gray. The floor of the white end box was 1½ in. below the runway floor. The black end box had a 2-in. hurdle at its entrance. The third end box had a level entrance and ¼-in. black-and-white vertical stripes. One 25-w. bulb hung 20 in. above the runway floor over each of the doors. This was the only illumination in the room. The *E* stood behind a 3 × 6-ft. copper screen that served as a partial one-way viewing screen.

The primary reward was 30-mg. cylindrical pellets made of six parts finely ground Purina Lab. Chow and one part flour. The rest of the daily ration was Purina Lab. Chow pellets.

Procedure

Five days before the experimental sessions, a hunger cycle of 23½-hr. deprivation and ½-hr. free feeding was established. On the third day, 10 hr. before feeding, *S*s were allowed to explore the runway in pairs for 15 min. with the door to the goal area closed.

Preliminary training.—On Day 5 the *S*s were assigned at random to the high- or low-reward group and given their first rewarded runs. During all experimental sessions *S*s were in individual cages and water was not available.

Each *S* was given six massed, rewarded trials on the first night. High-reward (HR) *S*s received four 30-mg. pellets on every rewarded trial and low-reward (LR) *S*s received one pellet. On all rewarded trials the white end box containing a glass food cup was used. Ten minutes after each experimental session *S*s were fed for ½ hr. in their home cages.

The response measure was the time to .1 sec. between the opening of the starting door and passage of *S*'s body through the second doorway. This was measured manually with a stop watch. Any *S* failing to pass the second door within 15 min. after the starting door was opened on any of the first three trials or within 5 min. on the last three trials on this first night was discarded.

Training.—For the next four nights each *S* received ten trials spaced 7 min. apart. Only six trials were rewarded and on nonrewarded trials the empty black box was used, in order to reduce generalization from the positive end box to other end boxes. The curtain prevented *S*s from seeing

[1] The first experiment reported here is part of a thesis submitted to the faculty of the Department of Psychology of the University of Missouri in partial fulfillment of the requirements for the M.A. degree, June 1952. The author is indebted to Prof. Melvin H. Marx for his advice and criticism. A report of the first experiment was read at Amer. Psychol. Ass., Washington, September 1952.

which box was in place before passing the second door.

The training pattern for a given set of *S*s was determined by random selection from one of 12 patterns that met the criterion of having the first and tenth trials always rewarded, and no more than two rewarded or nonrewarded trials in succession.

There was a total of 30 rewarded and 16 nonrewarded trials. On rewarded trials *S* remained in the end box for 20 sec., or until it had eaten all the food, which rarely took longer. On nonrewarded trials *S* remained beyond the second door for 15 sec.

Extinction.—On the tenth night each *S* was assigned at random to one of two extinction groups—with secondary reward (SR) or without secondary reward (NoSR). For the SR *S*s the white end box and an empty food cup, washed to eliminate food particles and odors, were in place. For the NoSR *S*s the black-and-white striped end box was used. This box, being dissimilar to the rest of the apparatus, was presumably neutral in reward value.

Each *S* received 30 massed extinction trials. When *S* passed the second door, it was detained for 15 sec., removed to a sawdust-lined metal bucket for 15 sec., then replaced in the starting box. When *S* failed to pass the second door within 2 min., it was given an arbitrary "running time" of 120.0 sec.

The *S*s were run in such an order that the mean number of hours of deprivation ranged from 23.78 to 23.94 for the four groups and did not differ significantly.

Results[2]

The groups were homogeneous in age and percentage of weight lost during the experiment but not in actual weight. HR–SR *S*s were significantly lighter than HR–NoSR *S*s ($t = 2.24$, $p < .05$), but LR–SR *S*s were heavier than LR–NoSR *S*s ($t = 2.50$, $p < .02$). The difference between HR and LR *S*s, however, was not significant.

[2] The major raw data and summaries of all data not given in the body of this report have been deposited with the American Documentation Institute. Order Document No. 4030 from Chief, Photoduplication Service, ADI Auxiliary Publications Project, c/o Library of Congress, Washington 25, D. C., remitting $1.25 for 35-mm. microfilm or $1.25 for 6 by 8-in. photocopies.

Twenty-two animals—18 LR and 4 HR—were discarded for failing to eat the pellets, failing to run, or for procedural errors. It was largely due to this high number of discards and the replacements necessary that the weight-difference source of error arose.

The differences between HR and LR running times on the last four training days were all significant at the 1% level of confidence and at the 5% level on the first day, with HR always faster than LR. Thus, the difference in amount of primary reward used was effective. The differences between running times of SR and NoSR *S*s within each of the reward groups on the final training day were not significant, neither *t* being as large as .80.

The extinction measure used was the number of responses made by each *S* that were not slower than the median running time (14.35 sec.) for all extinction trials for all *S*s. These scores ranged from 4 to 27, did not differ significantly from a normal distribution, and met the requirement of homogeneity of variance. In Table 1 the means for the four extinction groups are given. It was predicted that both SR groups would show greater resistance to extinction than their corresponding NoSR groups, and, if amount of primary reward affected secondary-reward strength, then the SR–NoSR difference would be greater in the HR group than in the LR group. The statistical analysis of these data was a 2×2 fac-

TABLE 1

EXPERIMENT I: MEAN EXTINCTION SCORES

Group	*N*	Mean	*SD*
HR–SR	16	16.56	5.15
HR–NoSR	16	13.00	4.54
LR–SR	16	16.44	6.71
LR–NoSR	16	14.00	5.70

torial design. In order to uphold the second hypothesis, a significant interaction variance should have been obtained.

Analysis of variance showed only one significant difference, that between SR and NoSR groups ($F = 4.33$, $p < .05$, for 1 and 60 *df*). Since weight correlated $-.36$ ($p < .01$) with extinction scores, a covariance correction was applied. Again the only significant difference was between presence and absence of secondary rewards ($F = 4.61$, $p < .05$). This experiment thus offers no evidence that secondary rewards associated with high or low amounts of primary reward differentially affect resistance to extinction. The presence of secondary-reward stimuli, however, was associated with greater resistance to extinction.[3]

Experiment II

Subjects and Apparatus

Twenty pairs of naive male albino rats from 90 to 130 days old and weighing between 138 and 224 gm. were matched for age and weight. Each pair was exactly the same age and no pair differed in weight by more than 10 gm. when matched at the beginning of the accommodation period.

All apparatus, including the food pellets, used in Exp. I was used in this experiment also. In addition, a U maze, with the same inner dimensions and same shade of gray as the runway, was used. The stem of this maze was 18 in., the crosspiece was 26 in., and the final stems at right angles to each end of the crosspiece were 12 in. long. Guillotine doors were located at the starting box, on both sides of the choice point, and at the end boxes.

Procedure

Most of the procedure employed in Exp. I was repeated in this study; only deviations from the earlier method are mentioned.

The amount of adaptation to the apparatus was increased to reduce the number of discards due to "nervousness." For three days, 12 hr. prior to feeding, *S*s explored the runway for 20 min. in pairs. The final adaptation period occurred only 12 hr. prior to the beginning of preliminary training. At this time one *S* in each pair was assigned at random to the HR or LR group, and its mate put in the opposite group.

Preliminary training was the same as in Exp. I. For the next four nights training trials in the runway were conducted as in Exp. I with two exceptions. The ten trials were now spaced 10 min. apart and turning-preference trials in the U maze were introduced before and after the training trials.

On the test night each *S* was given 16 trials in the U maze without primary reward. The white end box was in place on the nonpreferred side and the black-and-white striped box was on the other side. The *S*s were handled as during Exp. I extinction except that they were given 20 min. in which to enter an end box on any trial. Any *S* failing to enter an end box on every trial was discarded. HR and LR members of a pair were run successively in ABBA order.

Besides direction of turns, two running times were recorded: from starting box to end box, and from choice point to end box. These times were measured manually to the nearest .1 sec. by stop watches.[4]

Results

At testing, the mean weights of the HR and LR groups were 164.10 and 161.70 gm. ($t = 1.21$) and mean hours of deprivation were 23.75 and 23.70 ($t = .10$). Ten *S*s and their mates were discarded because of illness or for failure to meet the various criteria mentioned.

Differences between HR and LR transformed mean running times on the last four training nights were significant beyond the 5% level of confidence, again indicating that the difference in amount of primary reward was sufficient to produce a significant difference in the groups' response strengths in the runway.

[3] Possibility of a preference for the white box over the striped one was not checked and may have contributed to the SR–NoSR difference. However, other *E*s (e.g., 1) have established secondary rewards by procedures similar to those used here and it is unlikely that the obtained difference is entirely artifactual.

[4] The author wishes to thank Edwin B. Hutchins for his assistance in making these measurements.

TABLE 2

EXPERIMENT II: MEAN NUMBER OF TURNS TO NONPREFERRED (SECONDARY REWARD) SIDE OF U MAZE

Group	*N*	Mean	*SD*
HR	20	9.25	1.44
LR	20	9.05	0.97

The chief measure of secondary-reward strength was the number of turns to the nonpreferred side of the U maze. In Table 2 the means for the two groups are shown, based on 15 trials, since the first test trial was *S*'s first experience with the end boxes in place. By using matched-pairs analysis of variance an F of .20 was obtained, so the null hypothesis cannot be rejected.

Test-day weight and nonpreferred turns were correlated −.148. While not significantly different from zero, this r did reduce the power of the matched-pairs F test slightly, but negligibly, since the difference between groups was so small. By using an analysis-of-covariance correction for strength of original turning preference an $F = .06$ was obtained. There is again no evidence of a difference in secondary-reward strength due to amount of primary reward.

That both groups did learn a new response with only secondary rewards present was shown by the fact that 10 of 11 HR *S*s shifted from an original right-turning preference on the test night and 8 of 9 *S*s shifted from left to right, giving a $\chi^2 = 9.72$ ($p < .01$). In the LR group 9 out of 10 shifted from right to left and 10 shifted from left to right ($\chi^2 = 12.61$, $p < .01$).

Matched-pairs analysis of variance showed that only the running times from the choice point to the secondary-reward end box were significantly different for the two groups. The means of each *S*'s median running time were 4.71 and 2.74 for HR and LR groups ($F = 5.22$, $p < .05$). Since four different running times were analyzed and some significant differences are to be expected by chance, not much importance can be attached to this finding until it has been confirmed.

DISCUSSION

The results of these two experiments do not present any evidence that the strength of secondary-reward stimuli increases with increases in the amount of primary reward with which they are associated. The usual reservations about proving the null hypothesis, of course, apply here. In addition, two facts indicate that other factors may be operating in the situations studied.

In Exp. I the extinction scores reported were uncorrected for weight. Such a correction would make the LR–SR mean somewhat higher than the HR–SR mean, but not significantly. In Exp. II a related phenomenon was observed again. LR running times from choice point to goal were significantly faster. The reliability of this unexpected difference must be checked, however, before any speculations as to its origins are warranted.

SUMMARY

The relationship between strength of secondary reward and amount of primary reward with which the stimuli had been associated was studied in rats by two methods. In Exp. I secondary-reward strength was measured by the effect of such stimuli on the resistance to extinction of a simple running response. The groups receiving secondary reward differed significantly from the groups not receiving

secondary-reward cues, but the high and low secondary-reward groups did not differ significantly in resistance to extinction.

In Exp. II secondary-reward strength was measured by (*a*) number of turns to the nonpreferred, secondary-reward side in a U maze, and (*b*) running times in this apparatus. No differences in number of turns were found. Low-reward *S*s showed significantly lower median running times from the choice point to the secondary-reward end box, but no other running times differed significantly.

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RUNNING TIME AS A FUNCTION OF AMOUNT OF FOOD DEPRIVATION[1]

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This experiment was conducted to demonstrate the relationship between response strength and magnitude of hunger drive during testing, excluding effects of extraneous variables such as drive-stimulus generalization. Previous experiments in this area can be divided into three groups: (*a*) experiments in which all animals were trained under a single drive condition and then each tested under several drive conditions or separated into several groups to be tested under different drive conditions, thereby making it impossible to distinguish between the effects of changing the experimental conditions between training and test trials and the differential effects of the testing drives themselves (**4, 5, 7, 8, 10, 11, 12**); (*b*) experiments in which several training-drive levels were used and some animals from each training drive were tested under several drive levels, permitting statistical evaluation of the effects of training-drive levels, testing-drive levels, and interaction of training- and testing-drive levels (drive-stimulus generalization) (**13, 16**); (*c*) experiments in which training and testing were done under the same drive condition, this condition being different for each group of *S*s in the experiment. This method prevents drive-generalization effects but requires the assumption that the training drive has no effect upon response strength on test trials (**15**).

The present research follows a fourth type of design. In this experiment the variable of drive-stimulus generalization has been removed by prolonged training of every *S* under several drive levels before measuring response strength of each *S* under each drive level used in training. We assume that if sufficient training on any drive level is given to produce maximum response strength under that drive, no increment of strength can be added by generalization from another training drive. This procedure also permits a direct test of theoretical predictions of running times for individual animals as a function of the magnitude of drive.

Theoretical considerations.—The theoretical analysis summarized below is based upon Hull's theory as presented in *Principles of Behavior* (**6**). Since Burke (**2**) has already extended that theory by predicting the complete distribution of response latencies as a function of momentary effective reaction potential ($\hat{E}$), we have continued this development by restating Burke's equations in terms of the length of the period of food deprivation. The interested reader is referred to Burke's paper for a more extended treatment of the basic theory involved and to Cotton (**3**) for proofs of the equations below.[3]

[1] This article is based upon a thesis submitted to the faculty of the Graduate School in partial fulfillment of the requirements for the degree, Doctor of Philosophy, in the Department of Psychology, Indiana University. The author expresses his appreciation to Dr. C. J. Burke, under whose direction the thesis research was performed. He is also grateful to Dr. Burke and to Dr. B. J. Underwood of Northwestern University for their helpful suggestions made during the preparation of this article.

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[3] Our theoretical equations differ slightly from those of Burke and of Hull because we have assumed that the mean of the $\hat{E}$ distribution is $\bar{E}$, not $\bar{E} - 2.5\sigma$. This change has the advantage

Under the twofold assumption that inhibition (I) is zero and that S has reached the asymptote of the learning curve for a particular response, we state four major predictions relating running time (t), a measure of response latency, to the number of hours of food deprivation (h). The cumulative probability distribution function $G_2(t)$, the probability that the response latency will be less than or equal to t, is given by our equation (1) based upon Burke's equation (12).

As Burke has demonstrated, the mean and variance of the theoretical latency distribution do not exist although empirical values for both may be determined for any set of data in which infinite latencies do not occur. We have presented formulae for predicting the two measures of central tendency, the median and mode, which do exist in the theoretical distribution. We now indicate a means of predicting a variability measure for latencies in the theoretical distribution specified by equation (1). Equation (4) is a solution for the interquartile range, Q^1.

$$G_2(t) = 1 - \int_t^\infty \frac{a}{(t-t_0)^2} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{1}{-2\sigma^2}\left[\frac{a}{t-t_0} - m(\alpha+\beta h) - L\right]^2} dt. \quad (1)$$

The term t_0 is the physiological limit of response latency, a is an arbitrary constant yet unrelated to the theory, σ is the standard deviation of the E distribution, m is the habit strength obtained after prolonged training, L is the reaction threshold, and α and β are empirical constants depending upon the effects of h. This distribution curve resembles the normal ogive except that it lacks symmetry, having much greater curvature when $G_2(t)$ approaches 1.00 than when $G_2(t)$ approaches zero.

The median running time (t_1) under a constant deprivation condition is predicted by our equation (2), based upon Burke's equation (16).

$$t_1 = t_0 + \frac{a}{m(\alpha+\beta h) - L}. \quad (2)$$

The modal running time (t_2) is predicted by our equation (3) based upon Burke's equation (19).[4]

$$Q^1 = \frac{1.349\,\frac{a}{\sigma}}{\left[\frac{m(\alpha+\beta h)-L}{\sigma}\right]^2 - .6745^2} \quad (4)$$

The development of theoretical equations relating response latency to magnitude of drive is now complete. We know from Burke's experimental work (1) that his equations may be used to describe the running-time distributions obtained under a fixed deprivation schedule. Therefore, our evaluation of Hull's theory will depend primarily upon the degree of correspondence between the actual effects of changes in deprivation and the effects predicted by equations (1) through (4). In addition, purely empirical relations between deprivation and running time will be reported.

$$t_2 = t_0 + \frac{\sqrt{8a^2 + \frac{a^2}{\sigma^2}[m(\alpha+\beta h)-L]^2} - \frac{a}{\sigma}[m(\alpha+\beta h)-L]}{4\sigma}. \quad (3)$$

that it simplifies the theory without requiring any essential modification in the mechanisms postulated by Hull.

[4] The derivation of Equation 3 is that given by Burke in his equation (19), but a computational error which he made is corrected in the version given here.

METHOD

Subjects.—The *S*s in this experiment were two groups of ten male albino rats each, obtained from a commercial supply house. These *S*s were first placed under experimental conditions at the approximate age of 97 days.

Apparatus.—The apparatus consisted of a straight runway 10 ft. long with a starting box 1 ft. long and a goal box 1½ ft. long added to the runway proper. The inside width of the starting box and runway proper was 3¾ in. and the width of the goal box was 4¾ in. The inside height of the runway was 6 in. throughout. All parts of the runway were covered with Plexiglas.

The runway was illuminated by five 15-w. bulbs located 2½ ft. apart at a height of 11 in. above the runway top. No other lights were present during experimentation. A covering of cheesecloth extending on each side of the runway from the beam supporting the lights to the bottom (exterior) of the runway acted as a partial one-way vision screen. All experimentation was conducted in a sound-treated room in a relatively quiet area of the psychological laboratories.

A light source and a photoelectric cell were mounted on opposite sides of the runway at a distance of 1 ft. from a guillotine door separating the runway from the starting box. A similar unit was mounted at the same distance from the goal box. The two photocell units controlled the operation of a standard timer which registered the time required for an animal to traverse the 8-ft. distance between photocell units. A bottle of iodine solution between each light source and the runway acted as a filter to minimize the stimulation given *S*s by the light as it passed through the runway to the photoelectric cell.

A Mason fruit-jar lid placed at the end of the goal box opposite the door was used as a receptacle for the food pellets presented as reinforcements.

Procedure.—This experiment consisted of four phases: a pretraining period, a training period, and two test periods. The major difference between Groups I and II was that Group I was not given a second test phase. Except where a specific statement to the contrary is made, the reader may assume that each detail of the procedure applies to each group alike. Table 1 summarizes the experimental procedure described more completely below.

Preliminary training.—All *S*s were first placed under a food-deprivation schedule for 12 days. The schedule for each successive block of four days in this period was randomized, subject to the condition that the individual *S*s spend one day each under four deprivations: 0, 6, 16, and 22 hr. The number of hours of food deprivation (*h*) was controlled by allowing unrestricted eating during the interval from the end of an experimental hour until *h* hours before the next experimental period began. No forced-feeding methods were employed.

TABLE 1

EXPERIMENTAL PROCEDURE

Period	Drive	Group I (N = 10)	Group II (N = 10)
Pretraining		Days	Days
Deprivation and handling	Random	1–12	1–12
Partial runway trials	22 hr.	13–17	13–17
Training			
Complete runway trials	Random	18–61	18–61
First test period			
Complete runway trials	Random	62–97	62–93
Second test period			
Complete runway trials	Random	—	102–133

On the next five days of the experiment all *S*s were under 22-hr. deprivation at the experimental hour each day. On Days 13 and 14, each *S* was placed in the goal box individually five times daily, remaining there until either 5 min. had elapsed or a 43 mg. (dry weight) Laboratory Chow pellet had been consumed.[5]

On Day 15, each *S* made five reinforced runs through the last third of the runway and into the goal box. A block inserted at a distance of 3¾ ft. from the goal-box door prevented exploration of the remainder of the runway. On Day 16, each *S* made five reinforced runs through the last two-thirds of the runway and into the goal box. As before, a block was inserted to prevent exploration of the remainder of the runway. On Day 17, each *S* was given five trials through the complete runway, but with no delay in the starting box.

Training period.—On all days following pretraining the experimental procedure was constant except for changes in the drive condition assigned for each day. Ten rewarded trials, spaced at least 5 min. apart, were given each *S* on each day. For each trial, *S* was placed in the starting box for 5 sec. Then the starting box door was opened and *S* was allowed to run through the runway to the goal box for the customary reward. The *S* was removed 15 sec. later from the goal box and returned to an individual cage in the experimental room until the next trial.

With minor exceptions, the training period, extending from Day 18 through Day 61, consisted of 11 blocks of four successive days each

[5] Before the 5-min. criterion of noneating was established, *S*6 and *S*10 each spent two periods which exceeded 5 min. but did not exceed 10 min. before eating the pellet or being removed for noneating. All other trials conformed to the above procedure.

with each block involving a randomized sequence of the four deprivation conditions previously mentioned. The sole function of the training procedure was to enable all *S*s to reach peak running speed under each of the four drives so that data from a test phase could then be obtained.

First test period.—The purpose of the first test period was to provide data suitable for testing predictions based on Hull's theory. The deprivation schedule and experimental procedure of this period continued the pattern begun in the training period.

The first test period of this experiment extended from Day 62 until all *S*s in a group had made a minimum of 49 acceptable responses under each of the four drive levels. This required continuation of experimentation through Day 97 for Group I and through Day 93 for Group II. Responses were considered unacceptable when any one or more of the following six competing responses occurred during a run: retracing, face-washing, touching the cover of the runway, exploring the openings through which the photocell light beam passed, scratching self, and biting self. These responses were excluded from the theoretical phase of our analysis in the belief that a test of Hull's theory would be unduly complicated at this time by an attempt to study several competing response strengths simultaneously.

Some trials were lost because of mechanical failure of the timing circuit or when *S* jumped over a light beam and thus failed to operate the timer. These losses were most pronounced under the low drive conditions, being 2.0%, 1.7%, .2%, and .3% for the 0-, 6-, 16-, and 22-hr. conditions, respectively, with Group I. The corresponding losses for Group II were 5.0%, 6.0%, 2.5%, and .6%. The *E* believes that these losses were usually associated with exceptionally fast runs. Consequently, the mean running times reported for the low drive conditions may be slightly higher in relation to the other drive conditions than if these data had not been lost.

Second test period.—The purpose of the second test period was to provide a minimum of 49 additional acceptable responses per *S* under each deprivation condition in order to make further tests of Hull's theory. The second test period extended from Day 102 through 133 for Group II. Group I did not receive a second test period. Animals in Group II were run daily in the eight-day interim between the first and second test periods, but the data obtained were not considered usable because of a mistake in deprivation procedure on Day 96 and the possibility that running times on Days 97 and 98 were adversely affected by stimuli resulting from washing the runway. The deprivation schedule and experimental procedure continued as before.

The percentages of trials lost owing to timing-circuit failure or to an *S*'s jumping over the light beam were 8.8, 5.0, 1.4, and .4 for the 0-, 6-, 16-, and 22-hr. deprivation conditions, respectively. Two animals, *S*11 and *S*19, had losses of 22.5% of the data for the zero drive condition.

Results

First Test Period

The mean running time for each *S* was first determined for each day's performance. Then the average of the mean daily running times under each drive level was determined for each *S*. This was done twice: once using all the data available and once using the data from trials on which competing responses *did not* occur.[6] Trends based upon both sets of means will be reported, but all the tests of statistical significance described in this article are based upon the second set. Although less than ten running times were available for computing some of the mean daily running times, these means were themselves averaged without weighting. Consequently, the averages of the mean daily running times are not necessarily the same averages which would be obtained by totalling all available running times and dividing by the number of running times.

Relationships observed when competing responses were included.—The upper two curves of Fig. 1 present the averaged mean daily running times obtained for Groups I and II under each deprivation condition when no data were excluded from the analysis. Each group shows a trend toward faster running times with higher drive

[6] A two-page table giving these means and those for the second test period has been deposited with the American Documentation Institute. Order Document No. 4029 from Chief, Photoduplication Service, ADI Auxiliary Publications Project, c/o Library of Congress, Washington 25, D. C., remitting $1.25 for 35-mm. microfilm or $1.25 for 6 by 8-in. photocopies.

levels. All *S*s but one showed this trend in their individual means. *S*19 exhibited the opposite trend. The reader will note that, although the procedures for the two groups were almost identical, Group II running times are .7 sec. less, on the average, than Group I running times.

Relationships observed when competing responses were excluded.—The lower two curves of Fig. 1 present the averaged mean daily running times obtained for Groups I and II under each deprivation condition after trials involving competing responses were excluded. Again both groups show faster running times with higher drive levels. However, Fig. 1 shows that the range of group means for the four drive levels is now only .6 sec. for Group I and .4 sec. for Group II, compared to the 4.8 sec. obtained for each group before any running times were excluded. Furthermore, the exclusion of data obtained when competing responses occurred reduced all mean running times for each group. Again Groups I and II have different means, Group-II times being .8 sec. less on the average than Group-I times.

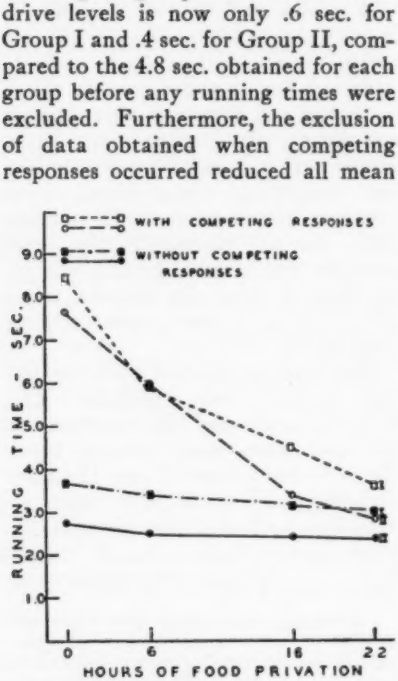

FIG. 1. The relationship between averaged mean daily running times and amount of food privation for Group I and II *S*s during the first test period

After the exclusion of data based upon trials involving competing responses, the means for individual *S*s are less consistent with the group trend toward faster running times with increased deprivation. In fact, *S*4, *S*5, and *S*19 showed the opposite trend, and *S*11, *S*12, *S*13, *S*15, and *S*16 showed almost no trend.

Testing the significance of differences between means.—An analysis of variance of daily means was performed for each group to test the effects of drives, *S*s, and interactions between drives and *S*s. These analyses are summarized in Table 2. Significant differences between performance on the four drives occurred in both groups. Thus neither of the lower two curves of Fig. 1 can be considered an approximation to a straight line of zero slope. Differences between individual *S*s were highly significant in both groups. A significant interaction between drives and *S*s (D × *S*) occurred in Group II only. These findings are to be viewed conservatively because the distribution of mean running times based upon ten or fewer trials is probably not normal.

Testing the running time distributions for randomness.—According to theory, Equations 1 to 4 are only applicable to data in which random variation (i.e., sO_R, Hull's oscillation function) can account for all the observed response variability. Therefore, it was necessary to determine whether or not the first test-period data for each *S* exhibit significant day-to-day changes or significant position effects within daily sessions before attempting to fit Equations 1 to 4 to the test-period data obtained for each *S*.

TABLE 2

ANALYSIS OF VARIANCE OF MEAN DAILY RUNNING TIMES OBTAINED IN THE FIRST TEST PERIOD

Source of Variation	Group I			Group II		
	df	Mean Square	*F*	*df*	Mean Square	*F*
Drives	3	6.86	5.36**	3	2.10	3.09*
Ss	9	12.50	9.77**	9	8.02	11.79**
D × *S*	27	2.21	1.73	27	1.62	2.38*
Error	320	1.28	—	280	.68	—
Total	359			319		

* Significant at .05 level.
** Significant at .01 level.

Eighty double-classification analyses of variance, one for each of the 20 *Ss* under each of the four drives,were performed with the original running times obtained in this period. Each analysis was performed by testing for row (position) and column (day-to-day) effects after all responses obtained from one *S* under one drive had been arranged in a table having ten rows for the number of trials per day and eight or nine columns for the number of days under each deprivation condition. When a score entry was missing because of competing responses or recording failure, the mean for that day was inserted in the blank. When the four analyses for each *S* were completed, an animal's data were classified as satisfactory for use in testing Equations 1 to 4 if not more than one of the four *F*'s for positions met the 5% level of significance nor any of the four *F*'s the 1% level. The same rules held for the four *F*'s for days. These criteria are based upon Wilkinson's table (**14**) stating the probability of obtaining *n* or more significant statistics in a group of *N* independent statistics. All *Ss* showed too many significant *F* values.

If any *S* showed position differences, the first or last trial per day was then rejected and four new analyses performed to show whether position effects remained. Sometimes two or more trials per day were removed before position effects were eliminated. Then day-to-day differences were reevaluated for the purpose of finding satisfactory animals for curve-fitting. Still there were none.

The analyses of variance just reported were also based upon nonnormal data. Since they served as an operationally defined basis for classification of data rather than for a clear-cut probability statement, this usage seems acceptable to us.

Second Test Period

The major purpose of this period was to obtain data which could be considered satisfactory for use in fitting theoretical curves. Until the completion of the analysis of the first test-period data for Group I, the need for this second test period was not known. At that time, only Group II was available for further experimentation.

As before, the mean daily running times for individual *Ss* were averaged for each drive level, once with all the trials included and once with the trials involving competing responses excluded. Again all tests of statistical significance are based upon data from

FIG. 2. The relationship between averaged mean daily running time and amount of food privation for Group II *S*s during the second test period

which the trials involving competing responses have been excluded.

Data for *S*18 are not included in our analyses because this animal made so many refusals to run under low drive late in the experiment that on two days no trials not involving competing responses remained to permit computation of a daily mean. Since this animal died of a respiratory infection less than a week after the experiment ended, illness is presumed to have produced this unusual behavior.

Relationships observed when competing responses were included.—The upper curve of Fig. 2 presents the Group II averages of the mean daily running times obtained under each deprivation condition without exclusion of any data. Again the group shows faster running times with higher deprivation levels. Two *S*s, *S*11 and *S*19, showed no consistent trend, but all others conformed to the group trend.

Relationships observed when competing responses were excluded.—The lower curve of Fig. 2 presents the Group II averages of the mean daily running times obtained under each deprivation condition after trials involving competing responses were excluded. This curve also shows faster running times with higher deprivation levels. However, the range of group means for the four drives is only .3 sec., compared to the 4.4-sec. range seen in the upper curve of Fig. 2 before any data were excluded. Five of the nine *S*s conformed to the group trend, but *S*11 showed the opposite trend, and *S*12, *S*16, and *S*19 showed no consistent trend of running time with drive level. Possibly *S*11 and *S*19 ran even faster under the 0-hr. drive condition than these data show, for we have previously noted a high percentage of data lost for these animals under that condition and have stated that these losses seemed to occur when the animals jumped over the photocell beam on exceptionally fast runs.

Testing the significance of differences between means.—Table 3 summarizes an analysis of variance of daily means performed to test the effects of drives, *S*s, and interaction between drives and *S*s (D × *S*). Significant differences between performance on the four drives and very significant differences between performances by the nine *S*s appeared. Interaction effects were not significant.

Testing the running time distributions for randomness.—Thirty-six double-

TABLE 3

ANALYSIS OF VARIANCE OF MEAN DAILY RUNNING TIMES OBTAINED IN THE SECOND TEST PERIOD: GROUP II

Source of Variation	*df*	Mean Square	*F*
Drives	3	1.90	3.52*
*S*s	8	10.99	20.35**
D × *S*	24	.62	1.15
Error	252	.54	—
Total	287		

* Significant at .05 level.
** Significant at .01 level.

classification analyses of variance, one for every S under every drive, were then performed with the original running times for the ten trials on each of eight days under each deprivation condition. These analyses were done in exactly the same manner as the similar analyses of the first test period. Four animals ($S11$, $S14$, $S16$, and $S17$) were found for whom daily variations and position differences were not significant. Therefore, these animals were considered satisfactory for use in further tests of Hull's theory.

Testing the predictions of the theoretical equations.—The cumulative curves to be fitted by Equation 1 were formed for each of the four satisfactory Ss by tabulating the percentage of actual running times at or below each of a series of fixed time values for each drive level. All running times obtained on trials in which competing responses occurred were excluded from these computations. Three terms $\left(\frac{m(\alpha+\beta h)-L}{\sigma}, \frac{a}{\sigma}, \text{and } t_0\right)$ were sufficient to determine the position and shape of the theoretical curve fitted to any set of empirical data. The curve-fitting was done visually. Figure 3 presents the fitted curves for $S14$, the animal which conformed most closely to theoretical predictions.

According to theory, t_0 and $\frac{a}{\sigma}$ should be constant for any S and $\frac{m(\alpha+\beta h)-L}{\sigma}$ should increase with h, the number of hours of deprivation. $S14$ meets these requirements fairly well, but the other three animals change their $\frac{a}{\sigma}$ values with changes in deprivation conditions. Poor fits were obtained when a constant $\frac{a}{\sigma}$ value was used for all four curves with any one of these animals. Attempts to fit

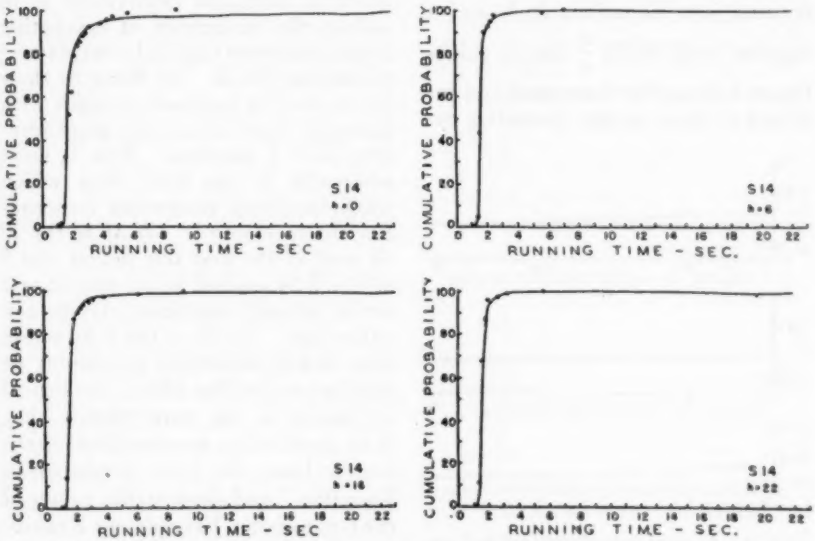

FIG. 3. A comparison of the cumulative running time distributions for $S14$ with theoretical curves fitted to those distributions

these curves with new t_0 values and constant $\frac{a}{\sigma}$ values also failed.

The final tests of the theory consisted of comparing the predictions of Equations 2, 3, and 4 with the actual median, mode, and interquartile range of running times obtained with *S*14 under each drive. Because the $\frac{m(\alpha+\beta h)-L}{\sigma}$ values for *S*14 (as well as for *S*17) did not always increase with increases in h, corrected values were estimated on the assumption that this parameter is a random variable for any h. A least-squares fit relating the h and $\frac{m(\alpha+\beta h)-L}{\sigma}$ values for *S*14 produced the following equation:

$$\frac{m(\alpha+\beta h)-L}{\sigma}=2.17+.03h.$$

Corrected $\frac{m(\alpha+\beta h)-L}{\sigma}$ values for each h were then determined and substituted into Equations 2, 3, and 4, together with *S*14's $\frac{a}{\sigma}$ and t_0 values. Figure 4 shows the theoretical and empirical medians, modes (including two modes for the 16-hr. condition), and interquartile ranges for *S*14. Although the medians and modes are underestimated slightly, a close correspondence between fact and prediction is evident.

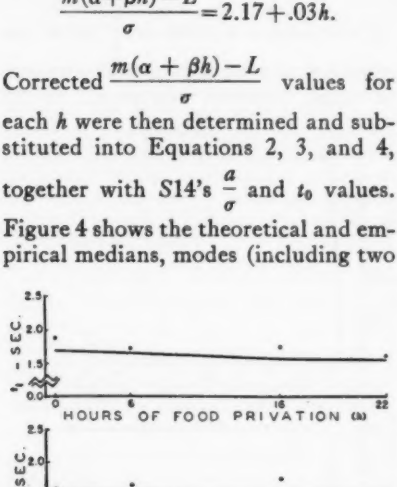

FIG. 4. A comparison of obtained and predicted values of the medians (t_1), modes (t_2), and interquartile ranges (Q^1) for *S*14

DISCUSSION

This experiment supports previous findings that response strength, which is inversely related to mean daily running time, increases with increased deprivation time. It also supports Burke's finding that his equations can be applied to the cumulative running-time distributions of animals tested after extended periods of training (1). Five features of our experiment are of particular interest: (*a*) Group trends cannot be attributed to drive generalization because all *S*s were trained under all four of the drive levels used during testing. (*b*) Removal of trials involving competing responses reduces the magnitude of the group trend appreciably, indicating that the major effect of increased deprivation is to reduce the occurrence of competing responses rather than to increase speed of running per se. (*c*) Some *S*s show no increase in response strength with increased deprivation, and some actually show a decrease. This is most noticeable in the data from which trials involving competing responses have been removed. (*d*) All of the 20 *S*s used in the first test period and 5 of the 9 *S*s studied in the second test period showed significant day-to-day variations. (*e*) All of the 4 *S*s whose data lacked significant day-to-day or position-to-position effects conformed to theory in the requirements that their cumulative running-time distribution have the form predicted in Equation 1 and show stable values of the t_0 parameter, but only one *S* exhibited stable values of the $\frac{a}{\sigma}$ parameter

used in fitting curves for different deprivation conditions.

The frequent occurrence of nonrandomness shown by significant day-to-day variations in the test-period data suggests three things: (*a*) *Ss* may not have been trained until their running times reached a minimum; (*b*) variables such as maturation may have produced nonrandomness; (*c*) a theory postulating random behavior after extended training may not be satisfactory.

The first possibility was evaluated by testing the hypothesis that the slope of the best-fitting straight line relating group mean running times to successive experimental sessions was zero (**9**, p. 296). This hypothesis was rejected in only two out of twelve cases: Group II showed a trend toward *decreased* running times as a function of practice under 22-hr. deprivation during the first test period, and toward *increased* running times as a function of practice under 0-hr. deprivation during the second test period. Consequently, the alternative (*a*) seems to have little validity for the first test period and none for the second. A choice between alternatives (*b*) and (*c*) cannot be made on the basis of present knowledge. However, alternatives (*b*) and (*c*) both have serious implications for Hull's theory. Alternative (*b*) leads to the conclusion that the theory is sound in principle but will lack predictive power until additional control of experimental conditions can eliminate nonrandom behavior. Possibility (*c*) flatly contradicts the theory. We must conclude that the applicability of the theory will be severely limited unless (or until) the conditions necessary for obtaining data without significant day-to-day changes can be specified.

The theory should also be modified to account for behavior of *Ss* who run faster under low drives than under high drives. Examination of Equation 2 shows that increased median running times should occur with increased drives whenever the ratio of $\frac{a}{\sigma}$ to $\frac{m(\alpha + \beta h) - L}{\sigma}$ increases with increased drives but gives no indication as to what controls the magnitude of $\frac{a}{\sigma}$.

Summary

Twenty male albino rats were first trained in a straight runway for 44 days under a randomized schedule of four deprivation conditions (0, 6, 16, and 22 hours). Then ten test trials were given per day until all *Ss* in each group of ten had made at least 49 responses not involving competing behavior under each drive condition.

Mean running times for both groups decreased in an approximately linear fashion with increased deprivation, whether or not trials involving competing responses were included in the computations. When these trials were omitted, the magnitude of the trend was markedly reduced, and three *Ss* showed a reversed trend.

To obtain data in which day-to-day variability was absent, the Group II *Ss* were continued for a second test period. Four *Ss* were continued for a second test period. Four *Ss* then met this requirement and were therefore judged acceptable for testing Hullian predictions regarding asymptotic behavior as a function of drive. One of these four conformed to theory very well. The running-time distribution for each drive could be fitted by the general theoretical equation, two curve-fitting parameters remained constant from drive to drive, and a third varied in accordance with theory. Predictions for the median, mode, and

interquartile range were of the same order of magnitude as the obtained values.

Data from the other three *S*s could be fitted with the general equation, but one additional parameter varied as a function of drive. The possibility that this parameter should be given theoretical significance as an indication of drive strength is mentioned but no such modification of Hull's theory is proposed at this time.

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S–R COMPATIBILITY: SPATIAL CHARACTERISTICS OF STIMULUS AND RESPONSE CODES[1]

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The present paper reports the results of two experiments designed to demonstrate the utility of the concept of stimulus-response compatibility[2] in the development of a theory of perceptual-motor behavior.

A task involves compatible S–R relations to the extent that the ensemble of stimulus and response combinations comprising the task results in a high rate of information transfer. Admittedly, degree of compatibility can be defined in terms of operations other than those used to secure a measure of information, for example, it could be specified in terms of measures of speed or accuracy. However, the present writers prefer the preceding definition because of the theoretican interpretation that they wish to give to compatibility effects. This interpretation makes use of the idea of a hypothetical process of information transformation or recoding in the course of a perceptual-motor activity, and assumes that the degree of compatibility is at a maximum when recoding processes are at a minimum. The concept of compatibility can be extended to cover relations between concurrent stimulus activities, such as take place during simultaneous listening and looking, as well as to relations between concurrent motor responses. However, the present paper will be limited to a consideration of stimulus-response compatibility effects in which the relevant information in the stimulus source is that generated by changes in its spatial characteristics, and the relevant aspect of a response is its direction of movement.

One of the earliest studies of the behavioral effects of changes in the spatial correspondence of S–R relations is the well-known experiment of Stratton (**12**) on vision without inversion of the retinal image. Recently the majority of studies of such effects have dealt with the spatial relations between machine controls and remote visual displays that are connected to them by mechanical or electrical means (**1, 3, 5, 9, 13**). These relations are important for human engineering. They have also become a matter of considerable interest for learning theory, in part because of Gagné, Foster, and Baker's (**2**) proposal that a reversal of S–R relations is the only condition leading to negative transfer effects in perceptual-motor learning. However, studies in both of these areas have consistently dealt with only one aspect of the compatibility problem. Investigations in the human-engineering area usually have compared different ways of displaying information when the *S* responds with a single type

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[2] The authors wish to credit Dr. A. M. Small for suggesting the use of the term *compatibility* in an unpublished paper presented before the Ergonomics Research Society in 1951.

of control, or else have examined the effectiveness of several kinds of controls or control motions when used with a single display. Investigations of transfer effects have typically considered only reversals of the stimulus-response relations within one S–R ensemble, such as changes in the direction of motion of the control on a particular psychomotor test (**8**), without specifying the location of the original task along a dimension of S–R compatibility. Only two studies (**7, 11**) have systematically investigated the effects of varying both stimulus sets and response sets. Such an approach is indicated by the concept of compatibility.

Information theory provides a convenient formulation of compatibility in terms of information coding. Shannon (**10**) and others have pointed out, in the case of physical communication channels, that information can be transmitted at a rate approaching channel capacity only if messages are optimally encoded for the particular channel being used. In such systems optimum encoding requires that messages be expressed in a suitable form and that their probability constraints be matched to the physical constraints of the channel. By analogy, it seems reasonable to hypothesize that man's performance of a perceptual-motor task should be most efficient when the task necessitates a minimum amount of information transformation (encoding and/or decoding), in other words, when the information generated by successive stimulus events is appropriate to the set of responses that must be made in the task, or conversely, when the set of responses is appropriately matched to the stimulus source.[3]

A few of the writers who have discussed the application of information theory to psychology have considered coding problems, such as the possibility of recoding as an aid in remembering. However, interest has been limited to stimulus coding (**6**).

Since the coding problem is central to the topic of compatibility, it will be worth while to consider briefly the available ways of choosing the sets of stimuli and the sets of responses employed in a visual-motor task. We shall consider only the case of a finite series of discrete code symbols. A stimulus code must utilize one or more stimulus dimensions such as the intensity, the wave length, the duration, or the extent of visible light. A unidimensional code is one in which the required number of unique code symbols is provided by the selection of points along a single stimulus dimension. A multidimensional code is one in which points are selected along two or more stimulus dimensions and each code symbol is defined by specifying a unique combination of several stimulus characteristics. In either case, several code symbols can be combined to form a larger multisymbol series.

A response code can be devised by similar procedures. A unidimensional response code utilizes a single effector member and a specified number of points along one of the physical dimensions of a particular response continuum, such as the direction, the force, or the duration of a movement. A multidimensional response code utilizes the complex response of a single effector member, such as the motion of the arm in positioning of a three-dimensional control, or the responses of several different effectors acting concurrently, such as the simultaneous responses of hands and feet in moving a set of conventional aircraft controls. Both the set of stimuli and the set of responses required in a particular task can thus be specified as

[3] If an incompatible S–R relation exists, then a considerable amount of recoding of information (such as the looking for meaningful associations, etc.) may be highly desirable.

points lying in the multidimensional space comprising the set of all possible discriminable stimuli and motor responses.

Garner and Hake (**4**) have pointed out that in order to attain maximum average information transmission per symbol, stimulus points should be selected with reference to their position along a scale of equal discriminability. A similar principle undoubtedly holds for the selection of a set of responses. Discriminability, defined without reference to response rate, establishes an upper limit to the maximum average information that can be generated by the selection of particular stimulus or response points from a set of points lying along a specified dimension. The problem of S–R compatibility remains, however, even when sets of stimuli and responses are optimally chosen with respect to discriminability. It concerns the question of how the correspondence of the sets of points in the stimulus and the response symbol spaces affects information transfer.

Experiment I

The first experiment was planned to test the hypothesis that, in tasks requiring directional motor responses to spatial stimulus patterns, effective performance depends to a large extent upon the unique characteristics of S–R ensembles rather than on specific aspects of particular stimulus or response sets. Three sets of stimuli (S_a, S_b, S_c), each comprising eight easily discriminable light patterns, and three sets of eight responses (R_a, R_b, R_c) were studied in the nine combinations formed by combining each stimulus set with each response set. Within each of these nine S–R ensembles, the pairings of stimuli and responses were those that the *E*s judged would be expected by most *S*s, i.e., would agree with population stereotypes. These sets of stimuli and responses were chosen as abstractions of commonly used spatial patterns of stimuli and responses, i.e., as familiar ways of representing points on a two-dimensional surface.

A further consideration in selecting the sets of stimuli and responses was that three of the nine S–R ensembles (S_a–R_a, S_b–R_b, and S_c–R_c) should represent "corresponding" permutations and combinations. Correspondence, in this case, was judged by the *E*s on the basis of the direct physical similarity of the two patterns. The experiment therefore provides an incidental test of how accurately S–R compatibility can be predicted from a consideration of the correspondence, with respect to the number of coding dimensions employed, between the two sets of points employed in stimulus and response coding.

Method

Apparatus.—The response required of *S*s was to move a stylus quickly in the direction indicated by a stimulus light or lights. The three stimulus and the three response panels used in the study are shown in Fig. 1 and a drawing of the *S*'s position, with the S_a–R_c combination in place, is shown in Fig. 2.

Stimulus Set *A* and Response Set *A* each consisted of eight permutations of direction from a central reference point. The stimulus panel contained eight lights forming the outline of a circle. The response panel contained eight pathways radiating from a central point like the spokes of a wheel. Each light and each pathway were separated from their neighbors by an angle of 45°. These stimulus and response patterns are characteristic of those provided by a pictorial azimuth or bearing display and an aircraft-type control stick.

Stimulus Panel *B* consisted of four lights separated by 90°. It provided four single-light positions, plus the four two-light combinations formed by adjacent pairs of lights. Response Panel *B* consisted of four pathways originating at a central point and separated by 90° intervals. Each path, as seen in Fig. 1, branched in a T and per-

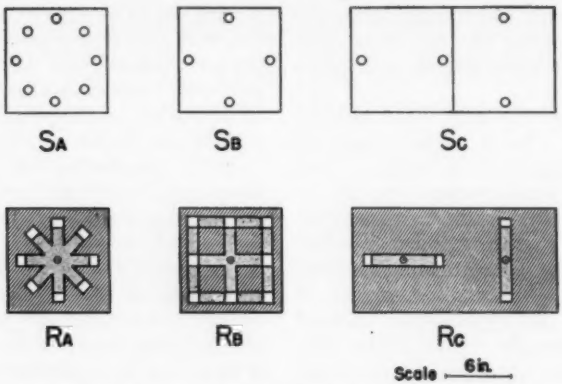

FIG. 1. The three stimulus panels (S_a, S_b, and S_c) and the three response panels (R_a, R_b, and R_c) used in Exp. I. The *S*s held a metal stylus on the circular button in the center of the response panel.

mitted *S*s to move from the center point to one of eight terminal positions. The four corner points of the response panel could be reached by two alternative pathways; for example, the upper-right corner could be reached either by a right-up sequence or an up-right sequence. The *S*s were told that these were equivalent responses. Response Panel B, therefore, involved the choice of a single directional movement, or of a sequence of two successive movements, and permitted *S*s to terminate their responses in one of eight end states.

Stimulus Panel C contained a pair of horizontally separated lights and a pair of vertically separated lights. The set of eight stimulus conditions that it provided included the four possibilities that a single light would come on, plus the four two-light combinations that could be produced by the simultaneous presentation of one of each of the two pairs. Response Panel C permitted a left or right response of the left hand, an up or down response of the right hand, plus the four possible combined movements of the two hands. Stimulus Panel C corresponds in general to two separate single-scale instruments and Response Panel C provides a set of responses similar to those present whenever two separate hand controls are used.

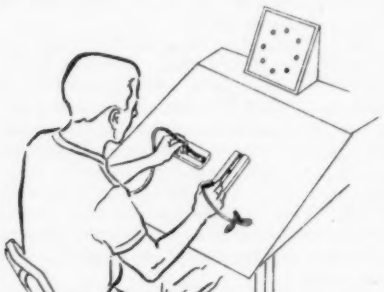

FIG. 2. The *S*'s station showing the correct two-handed response on Panel *C* to the lower right-hand light of Stimulus Set *A*

At the center of each response panel was a ½-in. diameter metal disc, surrounded by a thin nonconductive ring. Reaction time was measured as the time taken by *S* to move the stylus off this metal button.

The stimulus panels were mounted at a 60° angle to the horizontal. Response panels were 30° to the horizontal. The *S*s worked from a seated position. The stimulus panels were 15° downward and 28 in. from their eyes, and the response panels were at a convenient location in front of them. The *S*s watched the stimulus panels and seldom looked at their hands or the response panels.

The *E*'s station contained separate selector switches for the eight stimulus combinations and a single noiseless activation switch, which turned on the selected light(s) and simultaneously started a 1/100-sec. timer. The apparatus was designed so that different stimulus and response panels could be substituted at *S*'s station without any change at *E*'s station. The *E* sat where he could observe *S*'s movements and could record errors as well as reaction time.

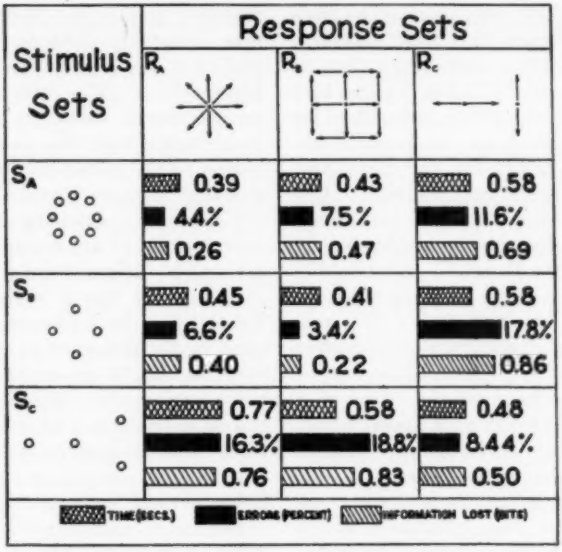

FIG. 3. Mean scores for the eight *S*s in each of the experimental groups. The datum for information lost is the theoretical information in the stimulus (3 bits) minus the computed value for information transmitted, uncorrected for sample size.

Subjects.—The *S*s consisted of 72 airmen at Lockbourne Air Force Base, selected on the basis of two-choice reaction-time measures.[4] Their ages ranged from 18 to 29 years. All were right handed. They were excused from drill during the time spent as *S*s and appeared to be well motivated.

The 72 *S*s were selected from a larger group of 153 men so as to form eight equal-sized strata which had homogeneous within-group average two-choice reaction-time scores. Each of the nine experimental groups was formed by drawing one *S* at random from each stratum. Each group of eight *S*s was then tested under one of the nine S–R combinations.

Procedure.—The instructions for each of the groups were similar. Those for the S_a–R_a group were as follows:

"Here is a stimulus panel of eight lights and a response panel in which you can move this stylus to one of eight places. Hold the stylus in your right hand. When I say 'center' place it on this center disc. I shall then say 'ready' and a few seconds later one of the lights will come on. If this light (point) should come on, move the stylus straight up. If this light should come on, move the stylus quickly to this position (indicate upper-right corner). If you start in the wrong direction, correct your movement as soon as possible. Do not try to guess which light will come on as they will be presented in a random order. Work for both speed and accuracy since both reaction time and errors will be recorded."

Each *S* was given 20 practice trials on his particular S–R combination, followed by 40 test trials. The order of stimuli was randomized, with the restriction of equal frequency for all stimuli at the end of each series, and a further restriction against runs longer than two.

Results

The experiment provides three measures of the effectiveness of each of the S–R ensembles: (*a*) reaction time, (*b*) percentage of responses that were errors, and (*c*) average information lost per stimulus. The means for all three criterion measures are indicated in Fig. 3.

[4] All *S*s were tested by the second author.

Reaction time.—In scoring the two-handed responses that were made on Panel *C*, reaction time was taken as the average of the times for the two hands. This procedure is justified by the finding that in two-handed responses the times for the right and left hands agree very closely. The average correlation of the two measures was .96 for the three groups that used Response Panel *C*, and the difference in the mean reaction time for the two hands was only .004 sec. However, for all one-handed responses on Panel *C*, the mean difference in reaction time between the two hands was .11 sec. in favor of the right hand, and 23 out of 24 *S*s using Panel *C* were faster when using the right hand. In summary, when *S*s had to move one hand alone, the right hand, which moved away from or toward the body, was significantly faster (by about .108 sec.) than the left hand, which moved to the right or the left, but when both hands had to be moved together, they had similar reaction times. The time for two-handed responses was approximately the same as the mean for one-hand responses by the left hand.

The means shown in Fig. 3 are for all stimuli in a set combined. The times for movements that were made in the wrong direction (errors) are combined with the data for correct responses, since the mean reaction times for erroneous and for correct responses did not differ significantly.

The mean reaction-time data for the different *S*s were tested for homogeneity of variance by Bartlett's test and no significant departure from homogeneity was found, even though variance tended to increase somewhat as the mean reaction time increased (the range of *SD*'s was from .036 sec. for the S_a–R_a ensemble to .097 sec. for the S_c–R_a combination). A double-classification analysis of variance for matched groups was then carried out (see Table 1). The most important finding is the highly significant interaction effect. The variance that can be attributed to interaction is very much larger than the variance attributable to the primary effects of either stimulus or response sets alone.

The differences in the means for the primary effects are interpreted as significantly different from chance, as indicated by the *F* ratios shown in Table 1 for which the residual term is used as the estimate of error. However, no reliable generalizations about these arbitrarily selected stimulus or response codes can be made to situations in which comparisons are made among different sets of stimuli or different sets of responses.

For every stimulus set there was a different best-response set, and for every response set there was a different best-stimulus set. For example, Response Set *A* led to the shortest mean reaction time in combination with Stimulus Set *A*, but to the longest reaction time in combination with Stimulus Set *C*. The difference of almost .4 sec. is 21 times as large as the estimate of the standard error of the difference. The three "best" combinations are those that were predicted by *E*s on the basis of the correspondence of the spatial codes. A

TABLE 1

ANALYSIS OF VARIANCE FOR THE REACTION-TIME DATA

Source	*df*	Mean Square	*F*
Matched *S*s	7	42896	
Stimulus sets	2	86772	68.43*
Response sets	2	36352	28.67*
S–R interaction	4	170492	134.46*
Residual	56	1268	
Total	71		

* Significant beyond the 1% level of confidence when tested against the residual as an estimate of error.

direct test of the significance of the difference between performance with corresponding and noncorresponding S–R ensembles is provided by a single-classification analysis of variance, which is equivalent to a conventional *t* test between the means for matched *S*s under the two conditions. Such an analysis was carried out and the difference was found to be highly significant ($p < .001$). The writers feel justified in predicting that if other sets of stimuli and sets of responses should be selected with due consideration to the correspondence of the stimulus and response codes, then it is highly probable that interaction effects would again account for a large portion of the variance and spatially corresponding codes would again give superior performance.

The reaction times for the S_a–R_a and the S_b–R_b combinations did not differ significantly, but both were superior to that for the S_c–R_c combination. It might be hypothesized that a bidimensional stimulus and response coding scheme (two pairs of lights and a two-handed response) is inefficient. It seems appropriate, however, to suggest an alternative hypothesis, that the inferiority may have been due to failure on the part of *E*s to observe some principle of response-response compatibility in selecting the eight alternative movements constituting Response Set *C*. It should be mentioned that forward and back responses made with the right hand only averaged .41 sec. for the S_c–R_c combination, which is comparable to the mean reaction times for the S_a–R_a and S_b–R_b combinations, where the right hand was also used.

Errors.—Approximately 10% of all responses were in error, an error being defined as an initial movement in the wrong direction. These error data agree in general with the time data in respect to the rankings assigned to the different S–R ensembles. The three "best" combinations within each row and column of Fig. 3 are the same for the two criteria. The difference between the best and the worst combinations appears to be relatively larger than was the case with the time scores. It is interesting to note that Response Set B, which in combination with its corresponding stimulus set (S_b) led to the fewest errors, resulted in the most errors when used in combination with another stimulus set (S_c).

The data for responses to separate stimuli revealed two important relations. The first is that those S–R ensembles having lowest mean error scores also tend to have the most uniform time scores from one stimulus to another. The second is that wherever there is marked variability within the responses to a set of stimuli, time and error scores tend to vary together, i.e., are positively correlated. For the four S–R ensembles with the greatest number of errors the rank correlations between time and error scores for the eight stimuli vary from .65 to .93.

Information lost.—The average information transmitted per stimulus was computed by Method 1 of Garner and Hake (**4**). The data for information lost, shown in Fig. 3, are the differences between the theoretical information in each stimulus event (3 bits) and the average information transmitted per stimulation.

The results of the information analysis agree closely with the total error frequencies and, in fact, add little to the grosser error analysis. The ranks of the nine groups are identical on the two criteria except for a reversal of the two last (worst) groups. This agreement is not surprising since the same type of error distribution, a piling up of errors in certain cells of the

matrix of transition probabilities, was found for all nine S–R combinations.

It is not possible to compute a meaningful estimate of average rate of information transfer in this experiment because of the relatively long time delay between successive responses. However, short response times were associated with small loss of information both within the eight conditions of each S–R ensemble and between the means for the nine different S–R ensembles. Thus the results of the information or error analysis, considered in relation to the reaction-time analysis, provide empirical support for defining compatibility in terms of the average *rate* of information transmission.

Experiment II

An important question concerning the results of the preceding experiment is whether the differences between various S–R combinations are transitory or permanent. An extended learning study was carried out in an effort to answer this question.

Method

The most desirable way to have conducted this study would have been to practice all of the 72 *S*s used in Exp. I over an extended period. However, this was not practical. Instead, a single new group was studied for 32 training sessions covering approximately 2½ months. The *S*s practiced making a single set of eight responses (Response Set *A*) to each of the three different sets of eight stimuli employed in the previous study. As an alternative *S*s could have been asked to make three sets of responses to a single set of stimuli, but this was not done because less initial habit interference is to be expected if the same responses are learned to three sets of stimuli, than if three sets of responses are learned to a single set of stimuli. Response Set *A* was chosen because there is no ambiguity in the scoring of these responses.

Six male students at Ohio State University were started on the training series but one dropped out after 20 sessions and his data are not reported (although they are comparable to the data that are reported). In order to maintain motivation *S*s were scheduled in pairs (except for the last 12 sessions of the odd *S*). One *S* was given a series of 16 trials on one of the three sets of S–R combinations in an unbroken sequence, while the other *S* observed. The *S*s then exchanged places. This procedure was continued until each *S* had been tested on each of the three stimulus sets. The sequence of work and rest and the order of trials on the three conditions were balanced. Each stimulus appeared twice in a random order within each run of 16 trials. Each *S* made a total of 48 responses per session.

Initial instructions and other procedures were the same as in the preceding experiment. At periodic intervals *S*s were cautioned to try not to make errors. In addition to reaction time and errors, *E* recorded movement time, the time to traverse the selected pathway of Panel A. After each response *S*s were told their reaction time and if they had made an error, this was pointed out.

On Sessions 27 to 30 inclusive, a secondary task, mental arithmetic, was carried on by *S*s concurrently with the perceptual-motor task. The *E* read aloud a series of numbers at a predetermined rate, and *S* gave the successive differences between the last two numbers read by *E*. This secondary task was introduced to test the hypothesis that the least compatible S–R combination would show the most deterioration under conditions of additional load or stress. Standard conditions were resumed on Session 31. The experiment was terminated at the end of Session 32.

Results

The mean reaction-time and movement-time data for the five *S*s are shown graphically in Fig. 4. Throughout all of the standard sessions performance was consistently best when *S*s responded to Stimulus Set *A*. Stimulus Set *B* gave almost equally good results. Stimulus Set *C* was much the worst of the three. At no time during the 32 days did any of the *S*s consistently respond as quickly to Stimulus Set *C* as they did to the other two sets of eight stimuli. The mean times for the three stimulus sets on Days 17 through 26 inclusive were as follows: S_a, .272 sec.; S_b, .286 sec.; S_c, .355 sec.

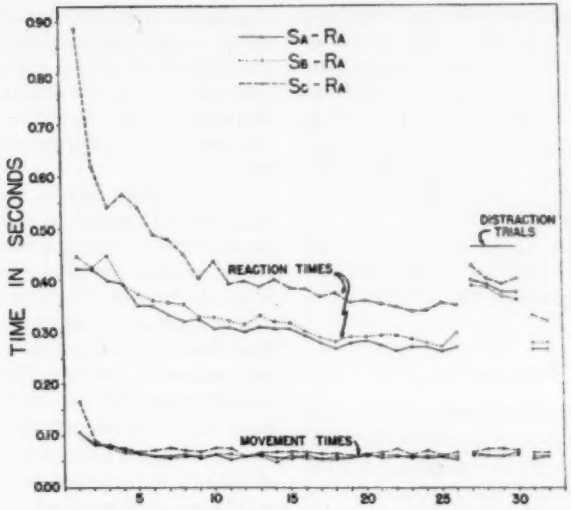

FIG. 4. Learning curve for five *S*s during the 32 training sessions of Exp. II. All *S*s had 16 practice trials on each of the three S–R combinations each session.

Movement time in responding to Stimulus Set *C* was slightly but consistently slower than to Sets *A* and *B*. Averaged over Trials 17 through 26 these times were as follows: S_a, .059 sec.; S_b, .061 sec.; S_c, .067 sec.

The error data, averaged over all five *S*s for successive blocks of time, are given in Table 2. It can be seen that the *S*s never succeeded in eliminating all errors. In fact, errors occurred more frequently as training progressed, indicating perhaps that *S* emphasized speed at the expense of accuracy. Errors were made most frequently to Stimulus Set *C* throughout the training period. Thus both time and error data indicate consistently poorer performance on the S_c–R_a condition.

TABLE 2

PERCENTAGES OF MOTOR RESPONSES THAT WERE IN ERROR DURING DIFFERENT BLOCKS OF TRAINING SESSIONS*

Sessions	S–R Combination		
	S_c–R_a	S_b–R_a	S_c–R_a
1–6	2.5	3.7	11.9
7–16	5.6	8.7	12.5
17–26	6.9	10.0	11.9
27–30**	4.4	6.9	15.6
31–32	8.1	9.4	12.5

* Sessions consisted of 16 responses per S–R combination for each of the five *S*s.

** On Sessions 27, 28, 29, and 30 the *S*s responded to stimulus lights and solved mental arithmetic problems concurrently. The number of arithmetic problems attempted during each session was 50 per *S* and the percentage of arithmetic errors for the three sets of stimulus lights was 4.1, 2.9, and 4.2, respectively.

On Days 27–30, when the load on *S*s was increased by the addition of a secondary task, reaction times were substantially slower for all three S–R combinations. All five *S*s continued to give the slowest reaction to Stimulus *C*; however, the relative differences between groups were much smaller than they had been previously. The frequency of arithmetic errors was approximately the same for all three groups, but there was a large differ-

ence between groups in the frequency of movement errors. The introduction of an additional task late in learning in this case apparently served to reduce the degree of readiness for the motor task, minimizing reaction-time differences, but increasing differences with respect to errors in the motor task. However, the data are not conclusive on these points and the test of the hypothesis regarding the effects of increased load is considered inconclusive.

Discussion

The results of the two experiments demonstrate clearly the importance of stimulus and response coding for the maximum rate of information transfer in a perceptual-motor task. It also is clear that some S–R compatibility effects are relatively unaffected by extended practice.

An interpretation of the basis for the relative permanence of these effects, which seems appropriate to the concept of compatibility, is one stated in terms of the capacity to learn to deal with sets of probabilities (probability learning). The response that a person makes to a particular stimulus event can be considered to be a function of two sets of probabilities; (*a*) the probabilities (uncertainties) appropriate to the situational constraints established by *E*'s instructions, by the reinforcements experienced in the experimental situation, and by other aspects of the immediate situation; and (*b*) the more general and more stable expectancies or habits based on *S*'s experiences in many other situations. It is suggested that extended training will nearly always lead to changes in the former but often will have relatively little effect on the latter.

This view holds that *S*'s behavior, notwithstanding long experience in a particular situation, is never entirely relevant to the specific constraints of that particular situation. Instead, *S* responds as if additional possibilities were present.

This interpretation supports the view that stimulus and response sets are optimally matched when the resulting ensemble agrees closely with the basic habits or expectancies of individuals, i.e., with individual and with population stereotypes. It must be remembered, however, that the expectancies referred to are those which hold for the particular situation under study, and that population stereotypes should be determined with due regard to the total situation. For example, in the present experiment the *E*s determined, by preliminary trial, that *S*s "preferred" to move toward rather than away from a stimulus light. However, it is known that in many stimulus tasks where the *S* controls the stimulus, the opposite motion relation is the expected one. When *S*s have to learn to deal with the probabilities inherent in a particular situation, the correspondence of these specific expectancies to the more general expectancies of the individual with respect to that kind of situation is an important aspect of the learning task.

Further support for considering S–R compatibility to be a function of stimulus and response matching comes from the positive correlation between the two criteria, time and errors, used in evaluating performance. This positive correlation would be expected if additional information transformations, or re-encoding steps, were added to a communication system, since each transformation would be likely to add an additional time delay and to in-

crease the total probability of errors. In the human it is hypothesized that the fastest responses may be the most accurate because they involve S–R ensembles in which the transfer of information from stimulus to response is most direct, i.e., involves the minimum number of recoding steps. The concept of intervening information transformations does not attempt to explain how such recoding occurs within the nervous system, but it is in agreement with the subjective reports of *Ss* who maintained that it was difficult, in the case of the less compatible S–R ensembles used in the present study, to be prepared to respond to all of the eight stimulus possibilities.

Summary

Experiment I was planned to test the hypothesis that information transfer in a perceptual-motor task is in large measure a function of the matching of sets of stimuli and sets of responses. Nine S–R ensembles, involving variations of the spatial patterns of stimuli and responses, were studied in an eight-choice situation, using groups of matched *Ss*.

The results, analyzed in terms of reaction time, errors, and information lost, support the hypothesis. They indicate that it is not permissible to conclude that any particular set of stimuli, or set of responses, will provide a high rate of information transfer; it is the ensemble of S–R combinations that must be considered.

Experiment II was planned to test the permanence of three selected S–R compatibility effects. Five *Ss* were trained for 32 days to make a particular set of responses to each of three sets of stimuli. Differences in reaction time, movement time, and frequency of errors in responding to the three sets of stimuli persisted over the 32 days.

The results are interpreted in terms of probability learning and the necessity for (hypothetical) information transformation or re-encoding steps. It appears that it is very difficult for *Ss* to learn to deal effectively with the information (uncertainties) characteristic of a specific situation, if these uncertainties are different from the more general set of probabilities which have been learned in similar life situations.

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ERRATUM

There was a typographical error in the article "The Effects of Single and Compound Classes of Anagrams on Set Solutions" by Irving Maltzman and Lloyd Morrisett, Jr., which appeared in the May issue of this JOURNAL (*J. exp. Psychol.*, 1953, **45**, 345–350). In Table 2 on page 347 the p value for the comparison between conditions ON–O and ON–ON was printed as .60. It should have been .06.

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